CIVIL ENGINEERING

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FINAL REPORT

RIGHT TURN ON RED: UTILIZATION AND IMPACT

TO: J. F. McLaughlin, Director
Joint Highway Research Project

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

June 23, 1976

Project: C-36-1700

File: 8-4-41

The Final Report attached titled "Right Turn on Red: Utilization and Impact" is submitted on the JHRP Research Study of the same title which was approved on June 4, 1975. The research and report were conducted by Mr. Michel S. Mamlouk, Graduate Instructor in Research on our staff, under the direction of Professor H. L. Michael.

The Report analyzes the use made of RTOR in Indiana one year after its initiation as a rule of the road. Substantial use is made of the maneuver, most traffic officials like it, few problems have occurred because of it, and restrictions to its use are located at about 12 percent of the approaches to a traffic signal. Between 3 and 4 percent of the total approach traffic save time through use of RTOR at the average signalized intersection.

The Report is submitted for acceptance as fulfillment of the objectives of the Study.

Respectfully submitted,

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RIGHT TURN ON RED: UTILIZATION AND IMPACT

by

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TABLE OF CONTENTS

	Page
LIST OF TABLES	v
LIST OF FIGURES	vii
ABSTRACT	viii
CHAPTER 1.. INTRODUCTION	1
CHAPTER 2. REVIEW OF LITERATURE	4
Present Use and Benefits	4
Accident Studies	7
Vehicle Delay and Travel Time	10
Capacity and Level of Service	12
Driver Compliance	14
Warrants	17
CHAPTER 3. DESIGN OF THE STUDY	22
1. Right Turn on Red	24
2. Left Turn on Red	31
3. Turn on Red Prohibition	33
CHAPTER 4. ANALYSIS	36
1. Right Turn on Red	36
Factors Affecting the Maneuver	36
Effect of Independent Variables	63
Traffic Conflict	69
Pedestrians	70
Driver Irritation	71
2. Left Turn on Red	71
3. Turn on Red Prohibition	73
CHAPTER 5. QUESTIONNAIRE ON RTOR	76
CHAPTER 6. FINDINGS AND CONCLUSIONS	83
BIBLIOGRAPHY	87

TABLE OF CONTENTS (Continued)

Page

APPENDICES

Appendix A - Locations from which the Data were Collected 90
Appendix B - Questionnaire on RTOR and Cities Replying 98
Appendix C - Statistical Analysis. 100

LIST OF TABLES

Table		Page
1	Measured Variables and Methods of Measurement for RTOR Study.	25
2	Physical Characteristics, Classes and Methods of Observations for RTOR Study. . .	30
3	Measured Variables and Methods of Measurement for LTOR Study.	32
4	Means and Standard Deviation of the Dependent Variables	37
5	Number of Studied Approaches Classified According to Intersection Characteristics, City Size, and Signal Type.	39
6	F-Values for Signal Type Tests.	42
7	Number of Studied Approaches Classified According to Intersection Characteristics and City Size	45
8	ANOVA Table for "Percent of Right Turn on Red", Model (1).	49
9	ANOVA Table for "Percent of Refused to Turn on Red", Model (1)	50
10	ANOVA Table for "Percent of No Chance to Turn on Red", Model (1).	51
11	ANOVA Table for "Percent of Right Turn on Red", Model (2).	57
12	ANOVA Table for "Percent of Refused to Turn on Red", Model (2)	58
13	ANOVA Table for "Percent of No Chance to Turn on Red", Model (2).	59
14	F-Values for the Different Variables for the Four Observation Hours.	67

LIST OF TABLES (Continued)

Appendix Table		Page
A-1	Cities, Intersections and Approaches from which the Data of RTOR were Collected	90
A-2	Cities, Intersections and Approaches from which the Data of LTOR were Collected	95
A-3	Cities, Intersections and Approaches from which the Data of TOR Prohibition were Collected	96
A-4	Expected Mean Squares of the Factors of Model (1)	101

LIST OF FIGURES

Figure		Page
1	Average Time Saved Per Right-Turn-on-Red Vehicles as Reported by May (21). . . .	11
2	Theoretical and Observed RTOR Volumes as Reported by Van Gelder (27).	13
3	Gaps Per Hour of Red Time Versus Cross Street Volume Per Hour of Red Time on the Approach for One Lane of Cross Traffic as Reported by May (10)	15
4	Gaps Per Hour of Red Time Versus Cross Street Volume Per Hour of Red Time on the Approach for More than One Lane of Cross Traffic as Reported by May (10) . . .	16
5	Cities of Indiana from which the Data were Collected.	23
6	Right Turn on Red Conflict (Braking). . . .	28
7	Right Turn on Red Conflict (Lane Change). .	29
8	Turn on Red Prohibition Sign.	34
9	Effect of Signal Type on Percent of RTOR Vehicles	43
10	Effect of Number of Approach Lanes on Percent of Vehicles Refusing to Turn on Red.	53
11	Effect of Exclusive Right Turn Lane on Percent of RTOR Vehicles.	61
12	Effect of Exclusive Right Turn Lane on Percent of No Chance to Turn on Red	62
13	Effect of City Size on Percent of RTOR Vehicles	64
14	Effect of City Size on Percent of Vehicles Refusing to Turn on Red.	65

ABSTRACT

Mamlouk, Michel Sobhi, M.S.C.E., Purdue University, May, 1976. Right Turn on Red: Utilization and Impact. Major Professor: Harold L. Michael.

The purpose of this research effort was to investigate the quality of use of "Right Turn on Red" in Indiana after one year of allowing the maneuver as a basic rule. Attention was given to the study of all factors that might affect the maneuver as well as the consequences that might occur as a result of applying it.

Data were obtained from 150 signalized intersection approaches scattered over 18 cities. Each approach was observed for four hours during peak and off-peak periods. The study examined the performance of the RTOR maneuver and the effect of the maneuver on traffic conflicts as well as pedestrians.

A part of the study examined left turn on red from a one-way street to another one-way street. The number of vehicles that turned on red at locations where RTOR or LTOR was prohibited was also observed.

A questionnaire was sent to traffic officials in the cities of Indiana to secure information and recommendations regarding the practice in their cities.

It was found that RTOR was made by 19.5% of the total right turns, while the LTOR was made by only 1.3% of the total left turns. The number of violations at locations where the turn on red movements were prohibited was very small, certainly insignificant.

Important factors that affected RTOR usage were: signal type, city size and availability of exclusive right turn lanes. The number of approach lanes and the number of cross lanes were of little importance.

Conflicts between turning on red vehicles and cross traffic did not cause a significant problem. Also, turning on red vehicles did not cause significant hazard to pedestrians.

Twenty RTOR accidents were reported in one year in over 70 cities according to questionnaire answers and interviews with traffic engineers. These accidents involved only minor property damages and minor injuries. Most traffic officials were in favor of allowing the RTOR maneuver as a basic rule. The only problem that was reported was that some drivers turn on red without coming to a complete stop before turning.

CHAPTER 1. INTRODUCTION

A primary function of the traffic engineer is to expedite with safety the movement of traffic. He must be alert to prevent unnecessary delays and to correct them when they do occur.

One delay which many drivers feel to be longer than necessary concerns standing at a red signal and being compelled to wait for the green light in order to make a right turn. Means for minimizing such delay, however, has fomented a great deal of argument among traffic authorities.

Laws, moreover, about allowing the "Right-Turn-on-Red" maneuver (RTOR) have changed considerably in the past few years throughout the country. As a result, present practices for the maneuver vary between states and between areas within a state.

The controversial problem of the RTOR began in 1937 when some authorities in California felt motorists intent on making right turns were wasting too much time waiting for the green traffic signal. At first these authorities permitted motorists to make a right turn while facing a red signal only when a sign was in place allowing such action (permission by exception). The driver was also required to stop first and yield to pedestrians and other vehicles properly approaching the intersection. In 1947 the state of California began permitting the RTOR movement at all signalized intersection approaches unless a sign was in place prohibiting the movement (permission by rule). Meanwhile, most other states prohibited the maneuver completely at all locations.

The RTOR maneuver in recent years has been permitted in some states while others continue to prohibit it. The result is that today the non-resident driver, faced with interpretation of and subsequent compliance with the practice as it is in the state in which he is driving reaches a dilemma over what to do.

As drivers have increased their area of travel over the years, the need for uniform standards for traffic control devices has increased. Since publication of the first edition of the Manual on Uniform Traffic Control Devices (MUTCD) in 1927, continued evolution of this standard handbook has occurred. In the 1954 MUTCD, the RTOR maneuver was highly discouraged because it weakened the clear meaning of the red indication.

Since there was little established evidence to counter the premise that RTOR might add hazard and delay when permitted, the 1961 MUTCD stated that permitting the maneuver was not recommended. The 1971 MUTCD, however, permitted the RTOR but only when a sign was in place permitting the turn. The driver was still required to come to a complete stop before making his turn.

In August, 1972, the National Highway Traffic Safety Administration (NHTSA) proposed in the Federal Register that all states would be required to enact legislation to permit the RTOR maneuver at all locations unless a sign was in place prohibiting the turn (5). Many traffic authorities, however, objected to this method of law making and the Institute of Traffic Engineers passed a formal resolution which opposed the method NHTSA was using to establish the use of the RTOR maneuver.

In Indiana, RTOR has been permitted by signs for many years but few intersection approaches had been so signed. On July 1, 1974, the RTOR maneuver was authorized by rule in the state of Indiana according to Public Law No. 82

which was enacted by the 1973 session of the Indiana General Assembly. This law states: "Where no sign is placed prohibiting such a turn, vehicular traffic facing a steady red signal, after coming to a complete stop, may cautiously enter the intersection to make a right turn... Such traffic shall yield the right-of-way to pedestrians and to other traffic using the intersection." By 1975 an excellent opportunity existed to evaluate use of the practice in Indiana and to ascertain the impacts and consequences of it throughout the state.

This study was therefore undertaken to collect and analyze data pertaining to the operation of RTOR as it had been allowed by the state of Indiana for almost one year. Attention was given to determine the different factors affecting the maneuver. Field surveys were taken in order to learn to what extent motorists have complied with the new law. Conflicts that might occur between vehicles that turned on red and the cross traffic were observed to determine the accident potential of such movement.

As a part of the study, a questionnaire was sent to the traffic authorities in cities of Indiana to determine the quality of use of the maneuver in each city. A further objective of the questionnaire was to secure opinions and recommendations from the traffic officials about the practice in their cities.

CHAPTER 2. REVIEW OF LITERATURE

The matter of RTOR has been examined in many studies. Some of these studies have been theoretical while others were reports of actual field surveys. At least one certainty exists, there is not total agreement regarding this maneuver.

The literature on RTOR can be divided into the areas of present use and benefits, accident studies, vehicle delay and travel time, capacity and level of service, driver compliance, and warrants for using the maneuver.

Present Use and Benefits

Upon reviewing the present use of the RTOR maneuver in the different states, one finds that one of three practices is followed:

1. Permission by "rule" - the driver is permitted to turn at all signalized intersection approaches against a red signal unless a sign specifically prohibits the movement.
2. Permission by "exception" - RTOR is allowed only at those approaches where a sign is in place permitting the maneuver.
3. Total exclusion - RTOR is prohibited at all signalized intersection approaches.

In the past few years, the permission rule has spread gradually throughout the states. As of April 1, 1976, thirty-six (36) state legislatures had passed legislation adopting RTOR by rule. The remaining fourteen (14) states permitted RTOR by signing and only the District of Columbia

did not permit RTOR in any form. Most state laws require the vehicle to stop first and yield to pedestrians and other vehicles legally using the intersection.

Obviously, final agreement between the states concerning the maneuver has not been reached. Authorities in states which either permitted or rejected the maneuver in the past could and did present reasons to support their action. As with almost every traffic control and regulatory measure each of these techniques has certain undesirable aspects. In 1968, the Institute of Traffic Engineers (4) reported that factors which have been used for the rejection of RTOR are as follows:

1. Vehicles, when turning right against a red signal are in direct conflict with pedestrians crossing with the green light on the opposite phase.
2. Vehicles abuse the full stop requirements.
3. RTOR results in a certain number of accidents involving pedestrians.
4. Either through deliberate abuse or poor judgment of what constitutes a safe gap in the cross street traffic, right turning vehicles which are relatively slow moving often force severe braking action to be taken by drivers proceeding along the cross street with the green. Inevitably, semi-broadside or rear-end collisions will occur.
5. In the C.B.D.'s of some cities during the peak hours of intersection use, one effect of permitting vehicles to turn right against the red signal may be an actual decrease in intersection capacity resulting from deterioration of progressive movements.

6. In the case of five- and six-leg intersections, offset intersections, special pedestrian phases, split phases, and multi-phase signal systems, it is often necessary or desirable to prohibit all or some approaches from turning right against the red signal. However, the appropriate sign is often difficult to position at these locations so that it will be easily observed and obeyed at all times by the driver.
7. Permitting the RTOR without a modifying arrow weakens the meaning of the red indication.
8. A traffic signal system should be complete in and of itself. It is wrong to provide one meaning to the motorist with a traffic signal and countermand that meaning with a sign.

Factors which support the use of RTOR were reported to be as follows:

1. RTOR minimizes a delay which is irritating to the motorist.
2. RTOR expedites the flow of traffic, thereby increasing intersection volumes and reducing congestion.
3. RTOR is not significantly hazardous, as accidents which involve vehicles turning right against the red signal have been found to be a small percentage of total accidents at signalized intersections.
4. Along major arterial routes with traffic signal progression in operation, the opportunity occurs for vehicles turning right from the various side streets against a red signal indication to enter immediately into the green band of the main street progression. On the other hand, those vehicles which turn into the main street during the side street green phase will be confronted with a red signal at the next signalized intersection along the main street.

Accident Studies

Accident analysis has been given the most consideration in the literature. This is undoubtedly because it reflects how safe the RTOR maneuver is. A study by Ray (21) in San Francisco Bay area in 1956 was one of the earlier studies dealing with the RTOR movement. In this study, accident reports at seventy-five intersections in three years were examined. The study indicated that:

1. Less than 0.3 of 1% of the overall accident experience could be attributed to the RTOR vehicles.
2. Less than 0.8 of 1% of the personal injury accidents included RTOR vehicles.
3. There was no significant increase in the hazard to pedestrians when RTOR was allowed.
4. No major personal injuries to pedestrians or people in the vehicles resulted from RTOR accidents.

The study concluded that RTOR contributed a very insignificant number of accidents to the total accident experience at intersections. Comparing the RTOR accidents to the RTOR volumes, it was concluded that RTOR accidents were 10.9% of the right turning accidents while the RTOR volume was 18.1% of the total right turning traffic. This indicates that RTOR was no more hazardous than RTOG. The general consensus of replies to a questionnaire used in the study was that the RTOR had not been a major factor in intersection accidents throughout the country.

In Santa Anna, California, Ray (22) conducted a survey of accidents involving right-turning vehicles at signalized intersections. The report showed no accidents involving a RTOR vehicle in the study period of two years and four months.

The effect of the RTOR maneuver on accidents was examined also in Colorado Springs, Colorado in 1966 (24). After about one year of operation there had been no accidents reported involving vehicles executing this maneuver. In this study, the RTOR maneuver was permitted only under the following conditions:

1. A regular high percentage (25%) of the total volume of vehicular traffic in a given direction turned right;
2. Regular delay of through traffic by the right turn movement and/or regular inability of the right turning vehicles to clear on the green phase;
3. Very low pedestrian counts;
4. Availability of a lane for the exclusive use of right turning vehicles;
5. Streets of sufficient width to accommodate the movement without undue or exceptional hazard, conflict or interference with other traffic; and
6. No unusual or exceptional obstruction to the vision of the turning driver.

A study was conducted in Los Angeles, California, and Scott (23) reported that RTOR accidents were less than 0.3 of one percent of all accidents at signalized intersections. However, RTOR vehicle-pedestrian accidents were slightly greater than two percent of the total vehicle-pedestrian accidents at all signalized intersections.

A before and after study was conducted by the Minnesota Highway Department at 197 intersections (12). The study found the following:

1. Direction of approach did not influence the occurrance of RTOR accidents.
2. Approaches involving moderate to heavy pedestrian volumes were relatively freer of RTOR accidents.

3. Approaches with moderate to heavy cross-street volumes had significantly more RTOR accidents than did approaches with low cross street volumes.
4. High volume right turn approaches had relatively more RTOR accidents.
5. There were significantly more RTOR accidents at approaches with two lanes of traffic approaching from the left than with one lane approach.
6. Approaches with phased left turns and with cross-street phased left turns had relatively fewer RTOR accidents.
7. Approaches with usable right turn lanes had significantly fewer RTOR accidents than did those approaches without right turn lanes.
8. Higher speed approaches had relatively fewer RTOR accidents.
9. Four-lane, two-way roadway intersections with four-lane, two way roadways had significantly more RTOR accidents.

Another study was conducted in Oklahoma City, Oklahoma, at approximately the same time (26). A before and after study indicated that the RTOR maneuver did not increase the overall accident problems at the studied intersections.

In a study conducted in College Station, Texas, Mathison (8) concluded that RTOR as a basic rule did not reveal any conditions where its use increased the accident hazards and that scattered increases in RTOR accidents could be attributed to lack of uniformity of application.

In a recent study conducted in West Lafayette, Indiana, May (10) reported that the total number of accidents at the study intersections did not increase. Neither, was there clear evidence that they decreased.

However, one study in Fort Lauderdale, Florida, reported an increase in accidents resulting from the RTOR

maneuver. In this study, May (9) reported that total accidents were increased by twenty-one percent at four intersections where the RTOR maneuver was permitted by sign.

From the previous studies, almost every study indicated that RTOR maneuver accidents were insignificant. In some reports, RTOR was proven to be no more dangerous than right turn on green and in fact possibly safer.

Vehicle Delay and Travel Time

The main advantage of the RTOR maneuver is the reduction of vehicle delay and travel time. This area has been given a lot of consideration in many studies. The basic reduction in delay is the time from when the vehicle makes a right turn while facing a red signal until the signal turns green for the same approach. In addition, the RTOR movement is claimed by some to reduce delay for through and left turn vehicles by clearing the approach and expediting the flow of all traffic. An indirect reduction in travel time may also occur for each vehicle which turns on red and enters into the green band area of a progressive signal system.

In the study conducted by Ray (21), on two-phase, fixed time signals, it was shown that delays to both peak and off-peak drivers were reduced with no additional delay observed to pedestrians or cross traffic. In addition, a correlation between the average amount of time saved per vehicle appeared to be directly proportional to the length of the red phase of the signal cycle as shown in Figure 1. An individual vehicle was found to reduce its delay at right turn signals as much as 66 percent during off-peak hours and 38 percent during peak hours. Ray found an average delay reduction of 9.6 seconds. He also found no significant decrease in running time, but a 7 to 10 percent

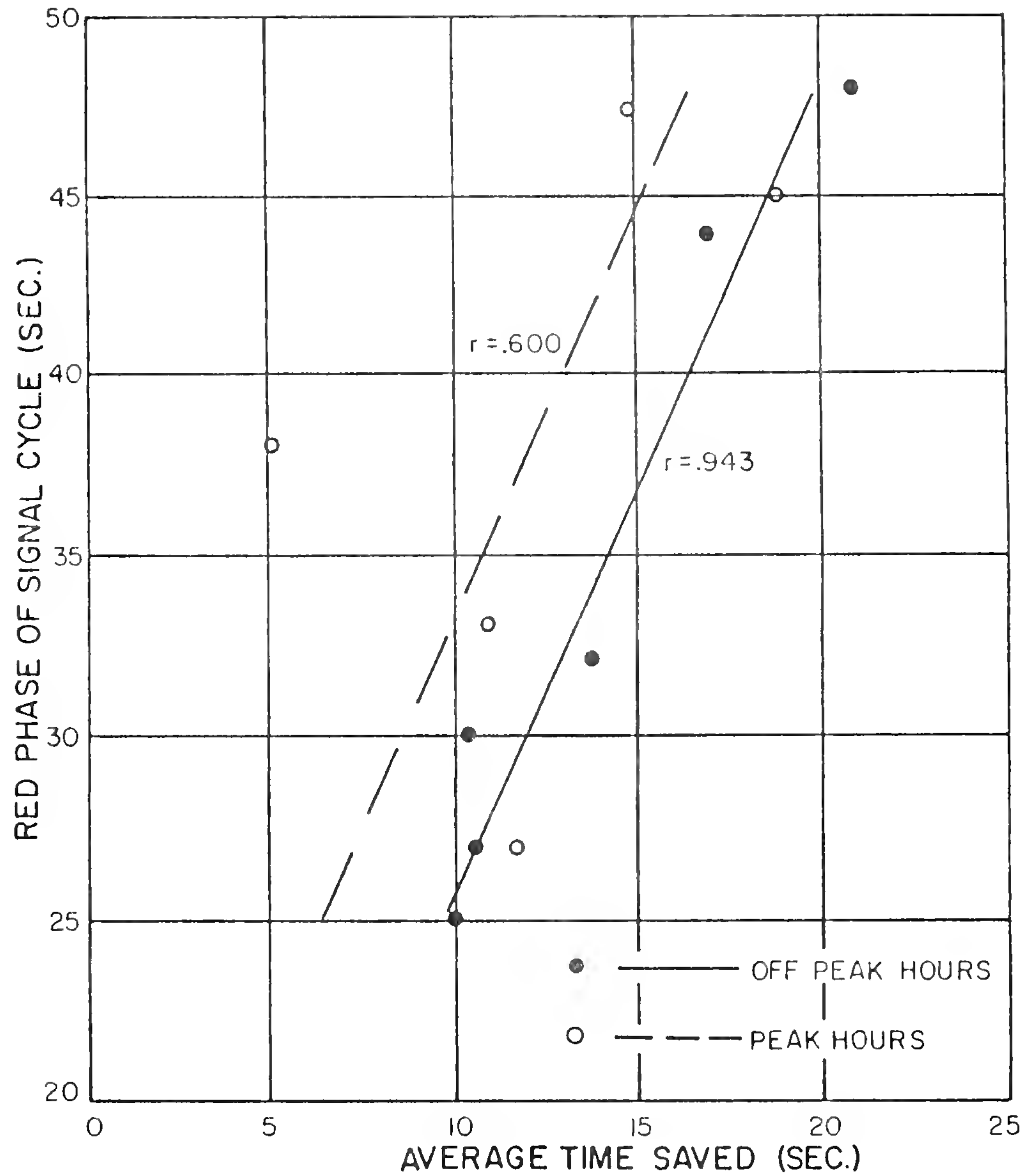

FIGURE 1. AVERAGE TIME SAVED PER RIGHT-TURN-ON-RED VEHICLE AS REPORTED BY RAY (21)

savings in overall travel time where RTOR was employed.

A study that was conducted by the Minnesota Highway Department (12) showed that the average reduction in vehicle delay was about 47 percent. This reduction was approximately the same for peak and off-peak periods as well as for fixed time and traffic actuated signals. Another study by the Minnesota Highway Department (11) emphasized the reduction in vehicle delay.

In New York, Van Gelder (27) conducted a study similar to the Ray study. He came to the conclusion that the RTOR maneuver had no effect on running time, he indicated a substantial reduction in travel time over the prescribed course.

May (10) concluded that no delays or hazards were encountered by the pedestrians as a result of the RTOR maneuver. Delay reduction to right turning vehicles was found to exist, but no means to predict the amount of delay reduction to be expected was developed.

Capacity and Level of Service

When RTOR is allowed, many suspect that the capacity of the intersection as well as the level of service of the several approaches would be improved. One study reported that the average traffic volume making a RTOR was about 18.1% of the total right turning traffic (21).

Through a theoretical technique, Van Gelder (27) developed a model to determine the increase in capacity resulting from the RTOR maneuver. The model was based on the assumptions that traffic stopped before making the right turn and that a continuous queue of right turning vehicles was present. When the model was tested with field data, it was found that it provided a reasonable estimate of the maximum limit of RTOR maneuver volumes. It was also found that the use of the RTOR maneuver did not increase

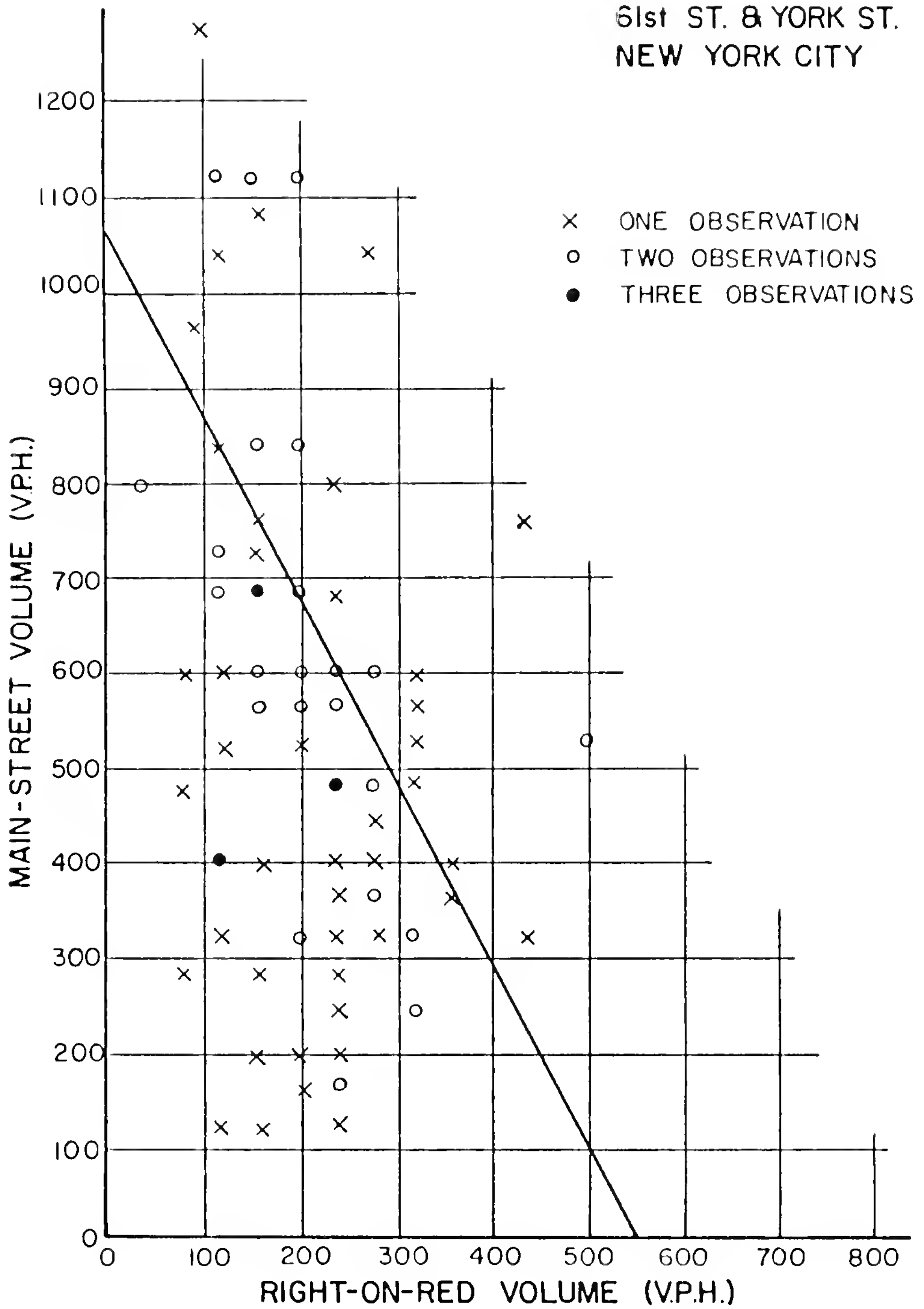

FIGURE 2. THEORETICAL AND OBSERVED RTOR VOLUMES AS REPORTED BY VAN GELDER (27)

the capacity of an intersection, but that it could improve the level of service of the approach when the cross street was not operating at capacity. The relationship between the RTOR volume and the main-street volume (cross traffic), as reported in this study, is shown in Figure 2. The straight line represents the maximum possible number of RTOR maneuvers when a continuous queue of right turning vehicles is present, while the plotted points are actual observations.

A controversial comment was made by Smith (24) in a magazine article. He wrote:

> "Assuming the average red time to be 30 seconds and assuming that each vehicle comes to a full stop at the stop-bar, only four or five vehicles at best will make the turn on the red phase. This is scarcely enough to warrant the permissive (permission by rule) regulation."

Such statements as this exemplify the continuing arguments over the practice of RTOR. Mathison (8) notes that if four or five vehicles can turn, an additional 240 or 300 vehicles per hour could move through the intersection, a substantial number.

May (10) developed a graphical relationship between the number of opportunities for vehicles to turn on red into the cross traffic, and the volume of vehicles on the cross street. Figures 3 and 4 show the gaps per hour of red time versus cross street volume per hour of red time on the approach.

Driver Compliance

A compliance study was conducted by the Minnesota Department of Highways (11). The study compared driver performance under permission by signing and permission by rule in the state of Minnesota. By means of field studies, right turning vehicles were classified as:

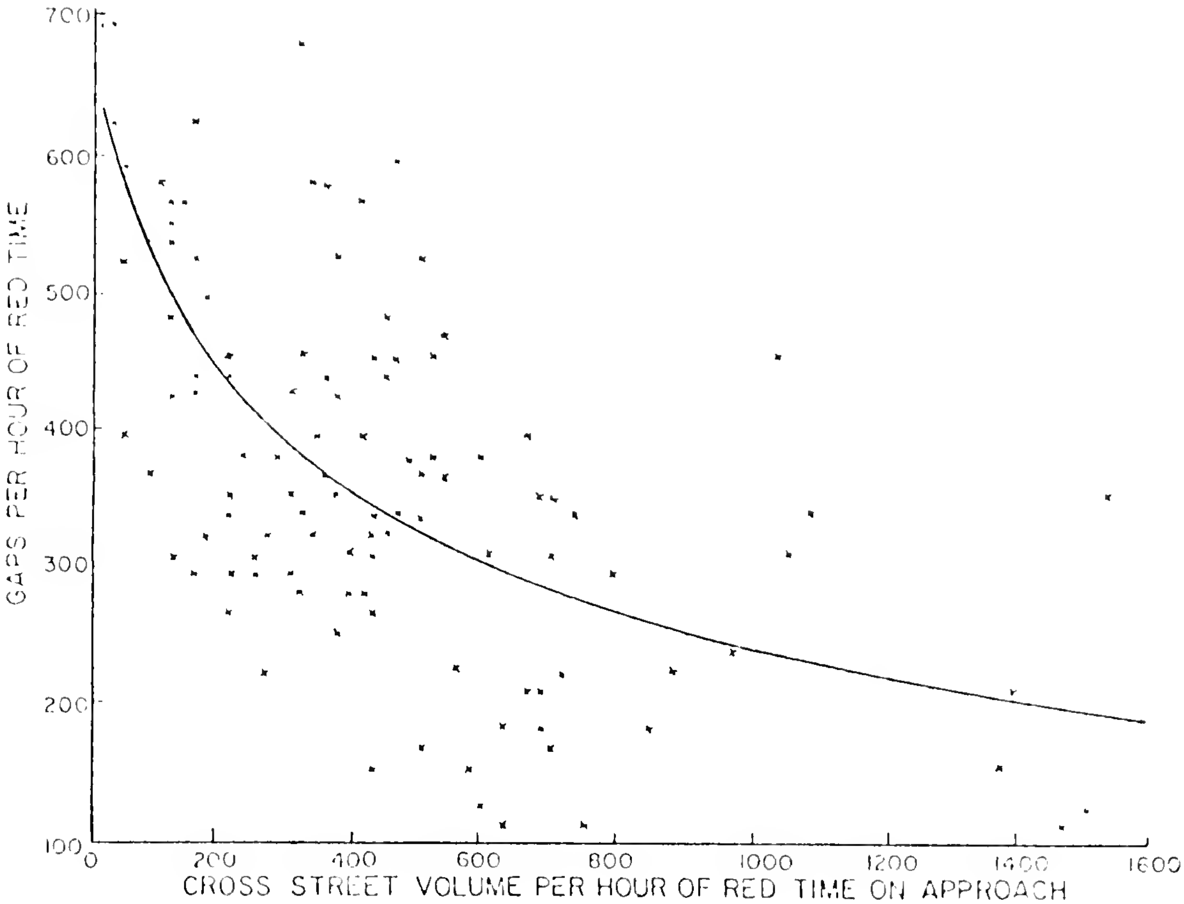

FIGURE 3 .GAPS PER HOUR OF RED TIME VERSUS CROSS STREET VOLUME PER HOUR OF RED TIME ON THE APPROACH FOR ONE LANE OF CROSS TRAFFIC AS REPORTED BY MAY (10)

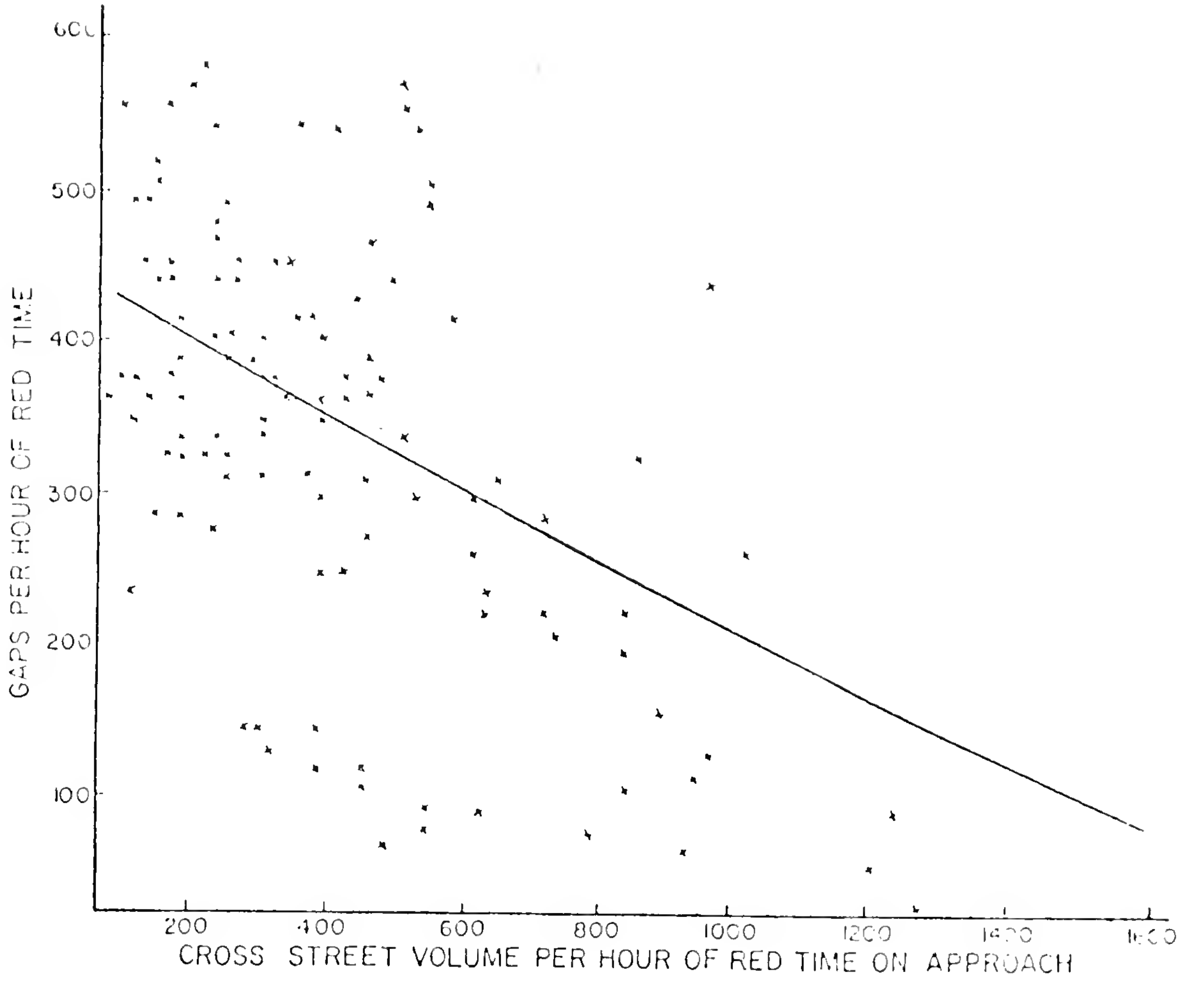

FIGURE 4. GAPS PER HOUR OF RED TIME VERSUS CROSS STREET VOLUME PER HOUR OF RED TIME ON THE APPROACH FOR MORE THAN ONE LANE OF CROSS TRAFFIC AS REPORTED BY MAY (10)

1. Turned on green.
2. Turned on red.
3. Refused the opportunity to turn on red.
4. Had no chance to turn on red.

The study also determined the percentage of drivers utilizing a legal RTOR, and also the percentage of drivers that performed RTOR at locations where it was not permitted. In general, the study found little difference in RTOR rejections for the permission by sign and permission by rule cases. There did appear to be more violations (illegal RTOR) with the rule case than for the sign case.

Warrants

Another important area of study has been to develop warrants for the use of RTOR. Some studies developed sets of warrants for this maneuver, but as yet there is no accepted standard followed by all states. In the study conducted by Ray (21), questionnaires were sent to some cities and states throughout the country. The results of this questionnaire indicated two sets of warrants for using the RTOR maneuver might be necessary, one for cities in the eastern part of the country and the other in the western part.

In the study by Smith in Colorado Springs, Colorado (24), some arbitrary warrants were established for the use of the maneuver. These warrants were listed in the accident discussion section of this report.

In Oklahoma City, Oklahoma (26), arbitrary warrants for prohibiting RTOR were established for the implementation of the RTOR maneuver at intersections used in their study. Also, some desirable and undesirable features for the application of the RTOR maneuver were reported by Mathison (8).

The Indiana State Highway Commission in 1973 (6), developed a list of criteria for not using the RTOR maneuver. According to that report, the maneuver should not be permitted:

1. In the CBD area with high pedestrian volumes.
2. At signals used by school children.
3. On approaches with only one approach lane.
4. On approaches with cross street volumes high enough to have no gaps available for safely performing the maneuver.
5. At high speed rural intersections.
6. At intersections with heavy truck movements.
7. At multi-legged intersections where the turn can be made into or from more than one approach leg.
8. At intersections with restricted sight distance.
9. At intersections where other protected movements are permitted under separate arrow indications.

The study of May (10) suggested some warrants for prohibition of the RTOR movement. These warrants were slightly revised by the Indiana State Highway Commission after further study and are subdivided into three groups:

A. TURNS ON RED should be prohibited for safety reasons where:

1. Minimum sight distance of cross street traffic as shown on the following Table, is not available to the potential TURN ON RED motorist.

MINIMUM SIGHT DISTANCE

SPEED OF CROSS STREET TRAFFIC	SIGHT DISTANCE IN FEET (APPROX.)
20	220
25	270
30	330
35	380
40	430
45	490
50	540
55	600

Minimum sight distance should be measured from the driver's position with the vehicle at a point immediately prior to entry into the intersecting street. Where pedestrian signals are in place, the sight distance should be measured from the driver's position with the vehicle at the STOP LINE, or if none, the CROSSWALK location. The engineering investigation should include an estimate of the approach speed of the crossing traffic since these speeds may be more or less than the posted speed.

2. A separate signal phase for a turning movement of which the TURN ON RED motorist may be unaware exists at the intersection, and which could conflict with a TURN ON RED movement; except when engineering investigations reveal that one of the following modifications to this warrant could be appropriate.
   (a) The warrants and need for the LEFT TURN ARROW should be considered and if the arrow is not warranted or is of minimum need, the arrow could be removed, and the TURN ON RED permitted.
   (b) When the left turn movement is fully warranted and made under a LEFT TURN ON ARROW ONLY situation, the conflicting RIGHT TURN ON RED maneuver should be prohibited; however, when two or more lanes are available to receive the left-turn vehicles, the TURN ON RED movement could be considered, depending upon the volumes of the respective turns and the lane widths involved. A minimum width of eleven feet is normally considered to be adequate for a lane.

(c) Where only one exiting lane is available to receive the left turn vehicle or where double lane left turn movements are permitted, the conflicting TURN ON RED maneuver should be prohibited, however, the movement may be permitted in special cases involving one-way streets and one-way interchange ramps where conflicts are minimal.

3. The intersection has more than four approaches. At such locations cross street traffic which conflicts with the TURN ON RED, may not be quickly identified by the TURN ON RED motorist or the TURN ON RED motorist may be able to turn into more than one street, thus creating unexpected conflicts.

   However, TURN ON RED maneuvers may be allowed at multi-legged intersections when it is apparent that no additional or unforeseen conflicts would be involved. For example, when the use of ONE-WAY streets would preclude traffic conflicts; where special channelization is in place, or where signal phasing is of such nature that conflicts are minimal.

B. TURNS ON RED may be prohibited because of little benefit from the maneuver at locations where:

1. There is a very short RED time for the approach;
2. Cross street traffic is heavy for many hours of the signal-operating day (where cross street is operating at capacity for many hours of the day);
3. Pedestrian use of the crosswalk on the approach is heavy for many hours of the signal-operating day;
4. Little right-turn demand exists and there is no RIGHT TURN ONLY lane available.

C. TURNS ON RED may be prohibited because of possible adverse public reaction where:

1. A school crossing route passes through the intersection;
2. There are moderate to high pedestrian volumes.

CHAPTER 3. DESIGN OF THE STUDY

In order to make a sound evaluation of the use of "Right-Turn-on-Red" after one year of allowing the maneuver as a basic rule in Indiana, field studies were performed in several cities of population more than 10,000 (Figure 5). These cities were located in all parts of the state so as to approach a random sample. An attempt was made to take all physical factors into consideration that might affect use of RTOR.

The field studies were divided into three major phases:

1. Evaluation of the right-turn-on-red maneuver at signalized intersection approaches where it was permitted.
2. Evaluation of the left-turn-on-red maneuver at signalized intersections of one-way streets where it was permitted.
3. Evaluation of turn-on-red prohibition at signalized intersection approaches where the maneuver was prohibited by signs.

The first phase was given the most consideration in the study because of the relatively wide use of RTOR. The LTOR maneuver was given less attention because of its infrequent use compared to that of the RTOR. The third phase also was not an extensive part of the study as the number of violations turned out to be very small. The data were collected during July, August and September of 1975.

FIGURE 5. CITIES OF INDIANA FROM WHICH THE DATA WERE COLLECTED

1. Right Turn on Red

Field observations were performed at 150 signalized intersection approaches where RTOR was permitted. The intersection approaches were picked at random from 18 different cities*. The characteristics of each approach varied widely from one location to another. Some of these approaches were near the central business districts while others were in fringe areas or residential areas. All the studied intersections were four-legged with either two-way or one-way traffic on each street. Volumes of traffic were high at some locations and low at others. The percentage of right turning vehicles was reasonably high in most cases. Pedestrian volumes were different from one intersection to another. At each one of the studied approaches sight distance was checked in order to make sure that it was adequate enough to allow the driver to turn on red safely if the gap in the cross traffic was sufficiently wide. All chosen intersections had two-phase signals. Some of the signals were progressive while most of them were non-progressive.

Several variables were measured in order to determine their effect on the performance of the RTOR maneuver. The different variables and methods of measurements are summarized in Table 1.

Referring to the data collection, a vehicle that did not have a chance to turn on red was recorded when the first vehicle in the right curb lane desired to turn right while facing a red traffic signal and there was no acceptable gap in the cross traffic during that red phase. Also, vehicles that were stopped behind the first vehicle in the queue while facing the red light and which desired to make a right turn were considered not to have the chance to turn

*For the list of cities and studied intersection approaches see Table A-1 in Appendix A.

Table 1. Measured Variables and Methods of Measurement for RTOR Study

Variable	Method of Measurement
<u>Right-Turn-on-Green</u>:	
1. Number of vehicles which did not have the chance to turn on red.	Manual Count
2. Number of vehicles which refused to turn on red when they had the chance to do so.	Manual Count
3. Number of vehicles which arrived on green.	Manual Count
<u>Right-Turn-on-Red</u>:	
1. Number of vehicles which turned on red and came to a full stop or very low speed before turning.	Manual Count
2. Number of vehicles which turned on red and did not stop (or slow to very slow speed) before turning.	Manual Count
<u>Total Traffic Volumes</u>:	
1. Total traffic volume on the studied approach (including right turning vehicles).	Traffic Counter
2. Total traffic volume approaching from the left (cross traffic).	Traffic Counter
<u>Signal Time</u>:	
1. Total cycle length.	Stop Watch
2. Length of red phase.	Stop Watch
<u>Traffic Conflicts</u>:	
Number of conflicts between RTOR vehicles and cross traffic.	Observation at Location

on red. It was not considered to be a "no chance" case unless the vehicle actually turned on green after stopping on red in either one of the previous two cases.

Vehicles that refused to turn on red were considered to exist when the first vehicle in the right curb lane turned on green after stopping for the red signal and remained stopped although it had the opportunity to turn on red. The opportunity to turn on red was a function of the availability of an adequate gap in the cross traffic. The decision of adequate gap was by judgment of the observer.

Observations were conducted on weekdays with data collected at both off-peak and peak hours. Off-peak hours were considered from 9:00 a.m. to 11:00 a.m. while peak hours were considered from 4:00 p.m. to 6:00 p.m. Results were recorded after each observation hour for both off-peak and peak periods.

Particular attention was devoted to examining traffic conflicts that might occur between RTOR vehicles and cross traffic. The traffic conflict technique developed by General Motors Corporation is a method of measuring traffic accident potential (18). Previous use of this technique has shown it to be a potentially valuable tool for the evaluation of intersection operation. It provides significant data in a short testing period. Moreover, studies have shown that conflicts and accidents are associated (1, 16).

As definition for this technique, there are five conflict categories: left turn, weave, cross traffic, rear-end, and violation. A cross traffic conflict is caused by a vehicle crossing or turning into the path of a through vehicle that has the right-of-way. That category was the one of interest in this research. The traffic conflict is identified by observing:

1. Evasive action of drivers to avoid a collision, and
2. Violation of traffic regulations.

Evasive actions are denoted by brake lights or lane changing; traffic violations are as defined in the Uniform Vehicle Code. RTOR, of course, could result in traffic conflict. If this in fact is the case, then the adoption of the RTOR maneuver might increase accident potential.

For a meaningful evaluation of the RTOR maneuver it was believed that the information which could be obtained from the traffic conflict technique would be more reliable than that available from accident history. Accident data may be inadequate, distorted, incorrect or incomplete, while traffic conflict studies use objective criteria to obtain significant quantities of data in short observation periods.

Observation of conflicts was conducted during the same times as observation for other data. Conflicts were observed from a vehicle parked on the side of the roadway about 100 to 300 feet prior to the intersection (Figures 6 and 7). The vehicle faced the direction of traffic movement and did not interfere with normal movements.

Physical characteristics of the studied intersections, classes that were considered and methods of observations are shown in Table 2. Cities of population more than 25,000 were considered to be large while cities of less than 25,000 were considered to be small.

At locations where pedestrian volumes were high, an attempt was made to ascertain the nature of conflict between vehicles turning right against the red signal and pedestrians crossing with the green signal. Pedestrian delay that resulted from the maneuver was also observed.

Drivers attempting to encourage vehicles in front of them to perform the RTOR movement were counted by recording the number of their horns that were sounded in that situation. The sounding of horns, of course, is not the only sign of driver irritation. However, it is the only

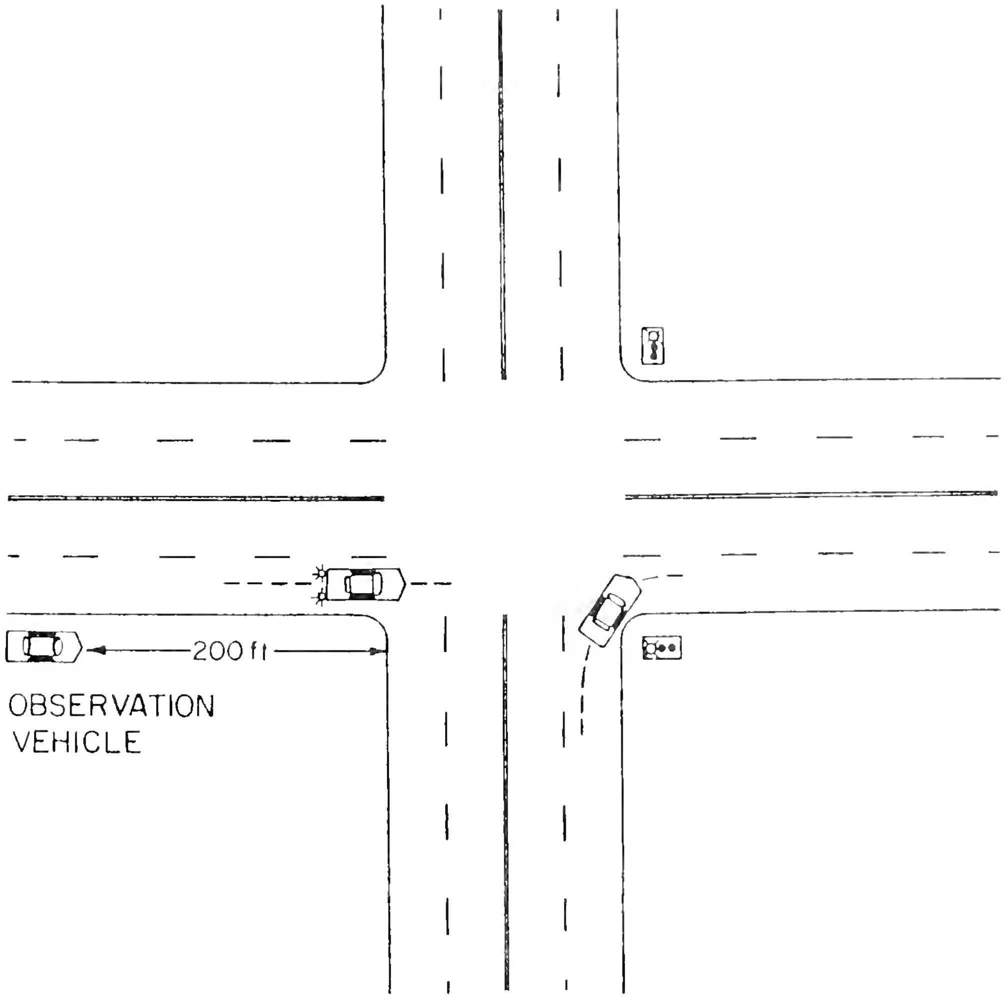

FIGURE 6 . RIGHT TURN ON RED CONFLICT
(BRAKING)

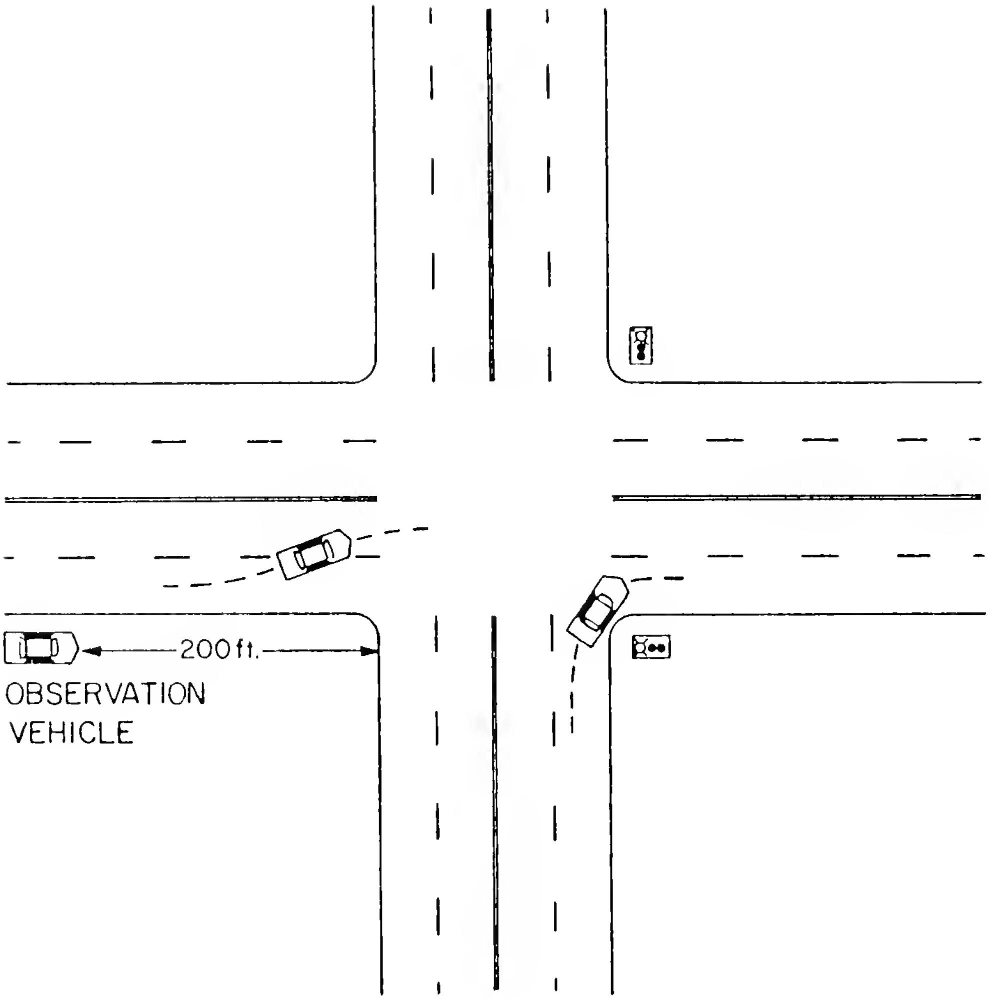

FIGURE 7. RIGHT TURN ON RED CONFLICT
(LANE CHANGE)

Table 2. Physical Characteristics, Classes and Methods of Observations for RTOR Study

Variable	Classes	Method of Observations
1. Number of approach lanes.	One lane or more than one lane	Observation at Location
2. Number of lanes of cross traffic upstream.	One lane or more than one lane	Observation at Location
3. Availability of exclusive right turn lane.	Available or not available	Observation at Location
4. City size	Large or small	Population records
5. Type of signal	Progressive or non-progressive	Observation at Location

indication that could be measured in this study.

Prior to the data collection, it was determined approximately how many observations would be needed to provide the desired degree of accuracy. Considering the large number of factors that were included in the study, it was determined that 150 signalized intersection approaches would be adequate.

2. Left Turn on Red

The policy of allowing the left-turn-on-red maneuver from a one-way street to another one-way street was adopted in Indiana as a basic rule concurrently with the adoption of the right-turn-on-red. All regulations applying to the RTOR were also applied to the LTOR. The regulations permit motorists to perform the maneuver between any two one-way streets with the flow of traffic at all locations unless there is a sign in place prohibiting it. The regulations also require the drivers to stop at first, yield the right-of-way to pedestrians and cross traffic, and then to make the left turn.

Field observations were conducted in an attempt to identify to what extent the drivers were acquainted with the LTOR movement. Eight signalized intersection approaches were chosen at random from four Indiana cities*. At every studied approach sight distance was adequate enough to allow the driver to turn on red safely if the gap in the cross traffic was acceptable.

The data were collected on weekdays from 9:00 a.m. to 11:00 a.m. and from 4:00 p.m. to 6:00 p.m. Different variables that were measured and methods of measurements are summarized in Table 3. Results of observations were recorded after each hour in both off-peak and peak periods.

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*For the list of cities and observed intersection approaches see Table A-2 in Appendix A.

Table 3. Measured Variables and Methods of Measurement for LTOR Study

Variable	Method of Measurement
<u>Left Turn on Green</u>:	
1. Number of vehicles which did not have the chance to turn on red.	Manual Count
2. Number of vehicles which refused to turn on red when they had the chance to do so.	Manual Count
3. Number of vehicles which arrived on green.	Manual Count
<u>Left Turn on Red</u>:	
1. Number of vehicles which turned on red and came to a full stop or very low speed before turning.	Manual Count
2. Number of vehicles which turned on red and did not stop (or slow to very slow speed) before turning.	Manual Count
<u>Total Traffic Volumes</u>:	
1. Total traffic volume of the studied approach (including the left turning vehicles).	Traffic Counter
2. Total traffic volume of the cross approach upstream.	Traffic Counter
<u>Signal Time</u>:	
1. Total cycle length.	Stop Watch
2. Length of red phase.	Stop Watch
<u>Traffic Conflicts</u>:	
Number of conflicts between LTOR vehicles and cross traffic.	Observation at Location

The same methods of measurements that were used in the RTOR study were also used in the LTOR study.

Conflict between LTOR vehicles and cross traffic was observed in the same manner as in the case of RTOR. The relationship between the LTOR vehicles and pedestrians was also observed.

The number of studied intersection approaches was small due to the small number of such intersections as well as the low frequency of LTOR performance in general.

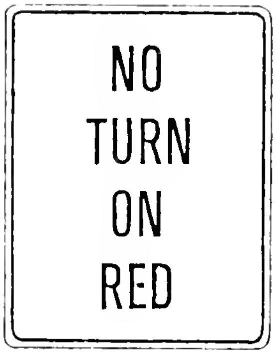
3. Turn on Red Prohibition

If RTOR or LTOR is not allowed at certain locations, a standard sign is required on each approach to prohibit the maneuver. The authorized sign is a regulatory sign with a legend NO TURN ON RED (Figure 8).

When applicable, this sign should be placed near the signal head which most directly controls the movement. It may be either an overhead mounting or a post mounted installation. This sign shall be placed only after an engineering and traffic investigation has been made which reveals the need for this regulation. Authorities having jurisdiction should not place this sign without the appropriate ordinance or resolution.

The turn-on-red prohibition is not normally applicable, nor required, for those right turns made behind a channelizing island where the movement is not controlled by the traffic signal, but by a "YIELD" sign, or where a right turn green arrow is displayed.

The turn-on-red maneuver should not be prohibited or allowed for specific times of the day, for specific types of traffic or vehicles, for specific days of the week, or for any other special classification or condition which would require the use of signs other than the standard NO TURN ON RED sign.



R-4
24" x 30"
Line 1—5"-5E
Line 2, 3, 4—4"-D

R-4A
36" x 48"
Line 1—8"-E
Line 2, 3, 4,—6"-D

White background with black legend
and border

FIGURE 8 . TURN ON RED
PROHIBITION SIGN

The turn-on-red prohibition should not be used at a location where other restrictions have been established which already prohibit that turn movement. The turn-on-red prohibition is not applicable when the signal operates as a flasher. Certain locations may require the prohibition of either a right turn or a left turn on red while the companion left turn or right turn is permitted. Special signs reading NO RIGHT TURN ON RED or NO LEFT TURN ON RED may be used as appropriate to post such restrictions.

The turn-on-red prohibition is not normally applicable where a right turn green arrow is displayed. A right turn arrow is a more positive control and its use is encouraged, particularly at locations having a separate lane for storing right turn vehicles, or where its use will minimize conflicts with other turn arrow movements and better utilize signal time.

Field studies were performed on a random sample of thirty-eight signalized intersection approaches in twelve cities in Indiana where RTOR or LTOR was prohibited*. It was desired to determine how the drivers complied with the system. Data were collected during one-hour periods on weekdays.

Prior to the data collection, the NO TURN ON RED sign was examined at each studied approach to determine whether it was properly signed. During the observation periods, the total number of right turn vehicles was recorded and also the number of violations (turn-on-red vehicles) was observed.

Different types of approaches were surveyed in an attempt to identify the conditions that may affect the number of violations. It was also desired to determine the difference in performance between properly signed and improperly signed approaches.

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*For the list of cities and studied intersection approaches see Table A-3 in Appendix A.

CHAPTER 4. ANALYSIS

The analysis of the study was performed as three major parts:

1. Evaluation of right-turn-on-red movement.
2. Evaluation of left-turn-on-red movement.
3. Evaluation of turn-on-red prohibition.

1. Right Turn on Red

The analysis was divided into several different items. These items are: factors affecting the maneuver, effect of independent variables, traffic conflict, pedestrians, and driver irritation.

Factors Affecting the Maneuver

One of the objectives of the study was to determine the different factors and variables that affect the following dependent variables:

1. RTOR vehicles as a percent of total right turning vehicles.
2. Drivers that refused to turn on red when they had the chance to do so as a percent of total right turning vehicles.
3. Vehicles that did not have the chance to turn on red as a percent of total right turning vehicles.

According to the collected data, the percent of right turning vehicles was different from one approach to another. For this reason it was decided to study the dependent variables as percentages of the total right turning vehicles rather than the total approach traffic volume. Means and

Table 4. Means and Standard Deviation of the Dependent Variables (in percent)*

Dependent Variable	Observation Hour	Mean	Standard Deviation
Percent of RTOR vehicles	1	22.49	15.39
	2	19.93	13.09
	3	17.08	11.77
	4	18.54	10.99
Percent of vehicles that refused to turn on red	1	11.44	10.62
	2	11.10	9.66
	3	8.75	7.25
	4	9.17	8.63
Percent of vehicles that did not have the chance to turn on red	1	15.13	10.98
	2	16.57	11.14
	3	22.72	13.67
	4	20.59	12.65

*All dependent variables were considered as percentages of total right turns.

standard deviations of the three groups in each of the four observation hours are shown in Table 4.

As an average of the four hours it was found that:

Percent of RTOR vehicles	=	19.5%
Percent of vehicles that refused to turn on red	=	10.1%
Percent of vehicles that did not have the chance to turn on red	=	18.8%

The remaining 51.6% represents the percent of vehicles that arrived and turned on green.

Average right turning vehicles were 19.0% of the total approach traffic volume. As a result the percent of RTOR vehicles represented only 3.7% of the total approach traffic volume.

The data that were collected from the one hundred and fifty approaches are classified in Table 5. The classification is based on number of approach lanes, number of cross lanes, availability of special right turn lane, city size and signal type.

The different factors that were considered in the analysis of the RTOR maneuver were:

1. Number of approach lanes (one or more than one).
2. Number of cross lanes (one or more than one).
3. Availability of special right turn lanes (available or not).
4. City size (large or small).
5. Signal type (progressive or non-progressive).

Also, three independent variables were considered in the study to determine their effect on the dependent variables. These independent variables were:

1. Traffic approach volume per lane (V_1).
2. Traffic volume per lane of the cross approach (V_2).
3. Signal red time phase as a percent of total cycle length (R).

TABLE 5. NUMBER OF STUDIED APPROACHES CLASSIFIED ACCORDING TO INTERSECTION CHARACTERISTICS, CITY SIZE, AND SIGNAL TYPE

Crossing Approach	One-lane Approach				Multi-lane Approach							
					No Special RT Lane				Special RT Lane			
	Small City		Large City		Small City		Large City		Small City		Large City	
	Non-Prog. Signal	Prog. Signal	Non-Prog. Signal	Prog. Signal	Non-Prog. Signal	Prog. Signal	Non-Prog. Signal	Prog. Signal	Non-Prog. Signal	Prog. Signal	Non-Prog. Signal	Prog. Signal
One-lane	9	0	8	0	3	0	7	3	1	0	3	0
Multi-lane	3	0	17	0	4	1	56	6	3	0	23	3

From Table 5 it can be seen that data of the progressive signal type were available only in four cells. Also, only a total of thirteen approaches are included in the four cells.

The first step of the analysis was to determine the effect of the signal type on the three dependent variables. Analysis of variance tests were performed to compare between approaches with progressive signals and approaches with non-progressive signals. Each cell including a progressive signal type was tested against the corresponding cell of non-progressive signal type, using the four hourly observations for each approach.

The tests were based on the following model:

$$Y_{ij} = \mu + P_i + \varepsilon_{(i)j}$$

Where:

Y_{ij} = the measured variable, i.e., percent of RTOR vehicles, percent of vehicles that refused to turn on red, or percent of vehicles that did not have the chance to turn on red.

μ = overall mean.

P_i = effect of the i^{th} signal type.

$\varepsilon_{(i)j}$ = within error, zero df, NID (o, σ^2).

The subscripts had the following values:

i = 1, 2.

j = 1, ..., 4 X number of approaches in each cell.

Foster-Burr test for homogeneity of variance was performed for the three dependent variables in the different cells. The results of the test are shown below:

Variable	$Q_{statistic}$	$Q_{0.01}$
Percent of RTOR vehicles	.135	.187
Percent of vehicles that refused to turn on red	.136	.187
Percent of vehicles that did not have the chance to turn on red	.132	.187

The assumption of the homogeneity of variance was accepted at 1% level of significance (28). Normality, additivity and independence of errors were assumed.

Table 6 summarizes the number of approaches that were used in each test and F values for each case. Tests of significance were performed at a 5% level of significance (α = 0.05). Significant and non-significant effects are denoted by the letters "S" and "NS", respectively.

For the percent of RTOR vehicles there were two significant F values, while the other two were non-significant. The number of observations was higher for the results which were significant, consequently these significant results were more dependable than were the non-significant. By calculating the average of the observed values in each cell, it was concluded that percent of RTOR vehicles is lower in progressive signal approaches than in non-progressive signal approaches. This is true because in the case of progressive signals most of the vehicles arrive on green and, consequently, the percent of vehicles that turn on green is high. Shown below are the averages of RTOR vehicles as percentages of total right turns for the four tested groups.

Group	1st	2nd	3rd	4th
Progressive signal approaches	4.0	15.6	12.5	7.2
Non-progressive signal approaches	11.0	21.3	19.9	26.0

The overall average of percent of RTOR vehicles was 11.3% for progressive signal approaches while it was 21.2% for non-progressive signal approaches. These results are shown in Figure 9.

The percent of drivers that refused to turn on red was found to be not affected by type of signal as shown in Table 6.

Table 6. F-Values for Signal Type Tests

Variable	No. of Progressive Signal Approaches	No. of Non-Progressive Signal Approaches	F-test	F-.05	Significance
Percent of RTOR	1	4	2.390	4.43	NS
	3	7	2.050	4.10	NS
	6	56	7.858	3.84	S
	3	23	25.797	3.96	S
Percent of refused to turn on red	1	4	.000	4.43	NS
	3	7	.027	4.10	NS
	6	56	2.510	3.84	NS
	3	23	.649	3.96	NS
Percent of no chance to turn on red	1	4	.002	4.43	NS
	3	7	.009	4.10	NS
	6	56	6.402	3.84	S
	3	23	1.572	3.96	NS

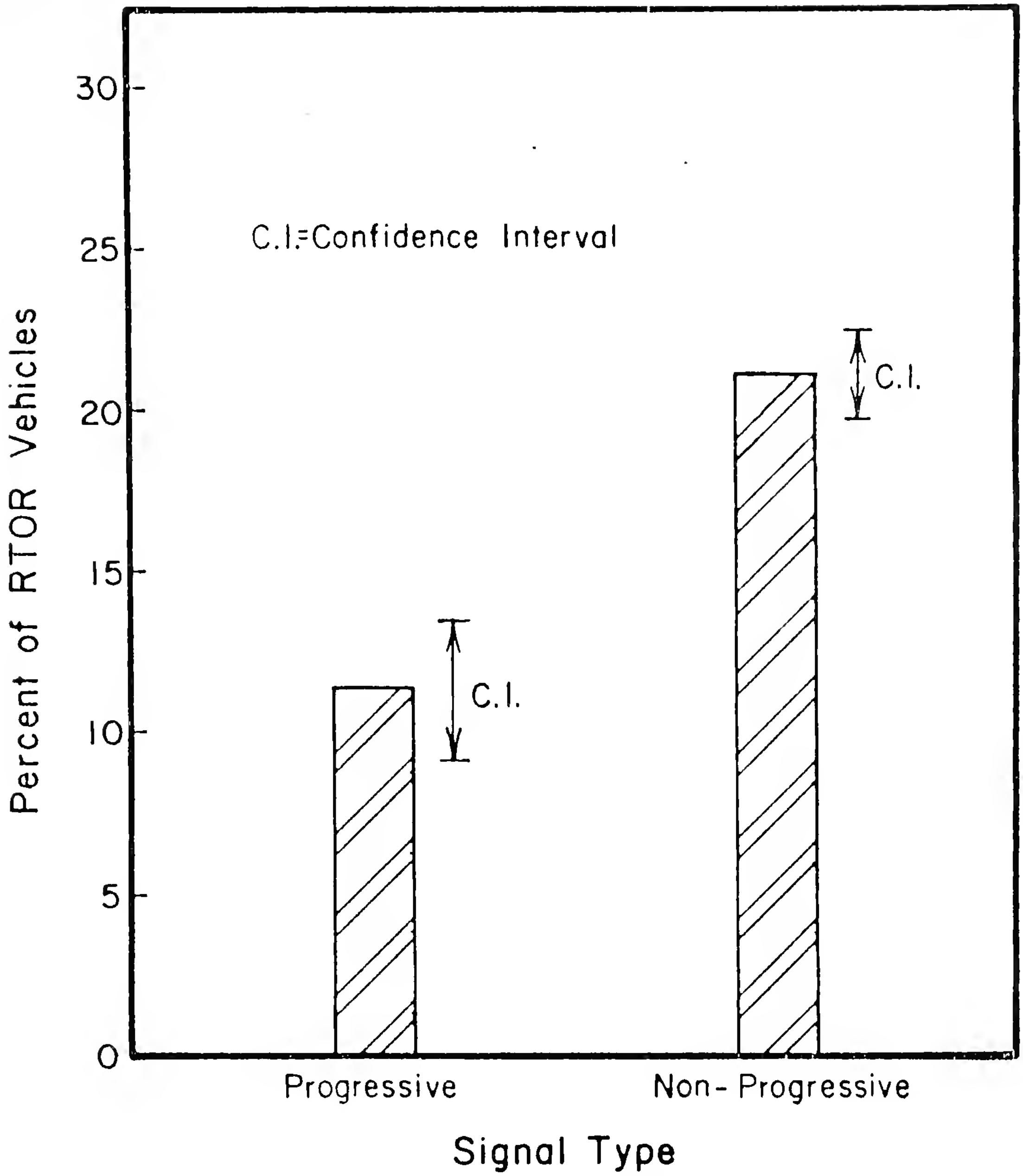

FIGURE 9. EFFECT OF SIGNAL TYPE ON PERCENT OF RTOR VEHICLES

As for percent of drivers that did not have the chance to turn on red, there were three non-significant values out of four. However, the F-value of the significant group was too large. Also, the number of the studied approaches in this group was larger than in the other groups. As a result the significant result was more reliable than the non-significant ones. In this case no definite conclusion was derived.

The second step of the analysis was to drop all approaches with progressive signals and take into consideration all other factors. The hundred and thirty-seven non-progressive signal approaches were classified according to intersection characteristics and city size as shown in Table 7.

Bartlett's tests for homogeneity of variance were performed for the three dependent variables in the twelve cells. Results of the tests gave chi-square values as follows:

Variable	χ^2-test	$\chi^2_{11,.99}$	$\chi^2_{11,.999}$
Percent of RTOR vehicles	15.0	24.7	31.3
Percent of vehicles that refused to turn on red	48.9	24.7	31.3
Percent of vehicles that did not have the chance to turn on red	25.6	24.7	31.3

The assumption of the homogeneity of variance was accepted for the first and third variables at α = .001 level (28). The homogeneity of variance was rejected for the second variable at α = .001 level. As a result, a transformation using the square root for the second variable was tried. The corresponding chi-square value was 18.1 which was accepted at α = .01 level indicating a Poisson distribution is involved (29). The transformed values of the second variable were used in the next analysis. Normality, additivity and independence of errors were assumed for this analysis.

TABLE 7 . NUMBER OF STUDIED APPROACHES CLASSIFIED ACCORDING TO INTERSECTION CHARACTERISTICS AND CITY SIZE

Crossing Approach	One-lane Approach		Multi-lane Approach			
			No Special RT Lane		Special RT Lane	
	Small City	Large City	Small City	Large City	Small City	Large City
One-lane	9	8	3	7	1	3
Multi-lane	3	17	4	56	3	23

In cases of one approach lane it is impossible to include exclusive right turn lanes for regular four-leg intersections. As a result, if one model of statistical analysis was tried, many missing cells could not be avoided. For this reason two different models were tried. The first model included all approaches that did not have exclusive right turn lanes and took into consideration all other factors and independent variables. Among the factors that were considered in this model was the effect of number of approach lanes. The second model included all multi-lane approaches and likewise took into consideration all other factors and independent variables. This model included the effect of the availability of an exclusive right turn lane which was not considered in the first model, but it did not include the effect of the number of approach lanes. Analysis of variance tests were performed on the two models in order to determine the significant factors in each case. An overall conclusion was derived using the results of both models.

Model (1):

Eight cells of data were analyzed by this model. The tested data were 107 approaches representing all approaches without exclusive right turn lanes. The model used was as follows: *

$$Y_{ijk\ell m} - \beta_1 V_{1ijk\ell m} - \beta_2 V_{2ijk\ell m} - \beta_3 R_{ijk\ell m}$$

$$= \mu + A_i + C_j + AC_{ij} + Z_k + AZ_{ik} + CZ_{jk}$$

$$+ ACZ_{ijk} + I_{(ijk)\ell} + \delta_{(ijk\ell)} + H_m + AH_{im} + CH_{jm}$$

$$+ ACH_{ijm} + ZH_{km} + AZH_{ikm} + CZH_{jkm} + ACZH_{ijkm}$$

$$+ IH_{(ijk)\ell m} + \varepsilon_{(ijk\ell m)}$$

---

*For more statistical details see Appendix C.

Where:

$Y_{ijk\ell m}$ = the measured dependent variable, i.e., RTOR vehicles as a percent of total right turns, vehicles that refused the opportunity to turn on red as a percent of total right turns, or vehicles that did not have the chance to turn on red as a percent of total right turns.

μ = overall mean.

A_i = effect of the i^{th} class of approach lanes.

C_j = effect of the j^{th} class of cross approach lanes.

Z_k = effect of the k^{th} city size.

$I_{(ijk)\ell}$ = effect of the ℓ^{th} approach in the i^{th} class of approach lanes in the j^{th} class of cross approach lanes in the k^{th} city size.

$\delta_{(ijk\ell)}$ = restriction error, zero df, NID (o,σ_δ^2).

H_m = effect of the m^{th} hour.

$V_{1ijk\ell m}$ = a measure of the approach traffic volume per lane of the i^{th} class of approach lanes with the j^{th} class of cross lanes with the k^{th} city size with the ℓ^{th} approach with the m^{th} hour.

$V_{2ijk\ell m}$ = a measure of the cross traffic volume per lane of the i^{th} class of approach lanes with the j^{th} class of cross lanes with the k^{th} city size with the ℓ^{th} approach with the m^{th} hour.

$R_{ijk\ell m}$ = a measure of the red signal time as a percent of total cycle length of the i^{th} class of approach lanes with the j^{th} class of cross lanes with the k^{th} city size with the ℓ^{th} approach with the m^{th} hour.

β_1, β_2 and β_3 = regression coefficients of V_1, V_2 and R respectively.

$\varepsilon_{(ijk\ell m)}$ = within error, zero df, NID (o, σ^2).

The other terms denote the interactions among the factors A, C, Z, I and H. The subscripts had the following values:

i = 1, 2

j = 1, 2

k = 1, 2

ℓ = variable (number of approaches in each cell)

m = 1, 2, 3, 4

In order to apply this model, linear regression equations were performed between the different dependent variables and the independent variables V_1, V_2 and R. The data showed that the linear relationship was the best fit. The effect of the independent variables was subtracted from the observed values of the dependent variables in order to determine the actual effects of the different factors.

In the ANOVA tests, the factors A, C, Z and H are fixed, while the factor I is random. Tables 8, 9 and 10 summarize the results of the analysis of variances for the percent of RTOR vehicles, the percent of vehicles that refused to turn on red, and the percent of vehicles that did not have a chance to turn on red respectively. Tests for the significance of main effects and interaction effects were performed at a 5% level of significance (α = .05).

Studying the different factors in the model indicates the following:

1. Time of the day did not have any effect on right turn vehicles in general because all the variation between hours was explained by traffic volumes and duration of red signal time.

TABLE 8. ANOVA TABLE FOR "PERCENT OF RIGHT TURN ON RED", MODEL (I)

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	EXPECTED MEAN SQUARES	F
FACTORS					
A	1	.021	.021	$4\sigma_I^2 + 16\ell\phi(A)$ †	.723
C	1	.036	.036	$4\sigma_I^2 + 16\ell\phi(C)$ †	1.239
Z	1	.374	.374	$4\sigma_I^2 + 16\ell\phi(Z)$ †	12.869*
H	3	.000	.000	$\sigma_{IH}^2 + 8\ell\phi(H)$ ‡	.000
2-WAY INTERACTIONS					
A,C	1	.026	.026	$4\sigma_I^2 + 8\ell\phi(A,C)$ †	.895
A,Z	1	.004	.004	$4\sigma_I^2 + 8\ell\phi(A,Z)$ †	.138
A,H	3	.002	.001	$\sigma_{IH}^2 + 4\ell\phi(A,H)$ ‡	.148
C,Z	1	.015	.015	$4\sigma_I^2 + 8\ell\phi(C,Z)$ †	.516
C,H	3	.010	.003	$\sigma_{IH}^2 + 4\ell\phi(C,H)$ ‡	.443
Z,H	3	.049	.016	$\sigma_{IH}^2 + 4\ell\phi(Z,H)$ ‡	2.360
3-WAY INTERACTIONS					
A,C,Z	1	.000	.000	$4\sigma_I^2 + 4\ell\phi(A,C,Z)$ †	.000
A,C,H	3	.019	.006	$\sigma_{IH}^2 + 2\ell\phi(A,C,H)$ ‡	.885
A,Z,H	3	.010	.003	$\sigma_{IH}^2 + 2\ell\phi(A,Z,H)$ ‡	.443
C,Z,H	3	.006	.002	$\sigma_{IH}^2 + 2\ell\phi(C,Z,H)$ ‡	.295
4-WAY INTERACTIONS A,C,Z,H	3	.030	.010	$\sigma_{IH}^2 + \ell\phi(A,C,Z,H)$ ‡	1.475
RESIDUALS					
I	98	2.848	.029	$4\sigma_I^2$	
I,H	295	2.000	.007	σ_{IH}^2	
INDEPENDENT VARIABLES	3				
TOTAL	427	5.490			

* SIGNIFICANT AT A 5% LEVEL OF SIGNIFICANCE.

† EXPECTED MEAN SQUARE TERM IS TESTED BY THE TERM (I).

‡ EXPECTED MEAN SQUARE TERM IS TESTED BY THE TERM (IH).

TABLE 9. ANOVA TABLE FOR "PERCENT OF REFUSED TO TURN ON RED", MODEL (I)

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	EXPECTED MEAN SQUARES	F
FACTORS					
A	1	.328	.328	$4\sigma_I^2 + 16\ell\phi(A)$ †	7.694*
C	1	.044	.044	$4\sigma_I^2 + 16\ell\phi(C)$ †	1.032
Z	1	.785	.785	$4\sigma_I^2 + 16\ell\phi(Z)$ †	18.413*
H	3	.000	.000	$\sigma_{IH}^2 + 8\ell\phi(H)$ ‡	.000
2-WAY INTERACTIONS					
A,C	1	.103	.103	$4\sigma_I^2 + 8\ell\phi(A,C)$ †	2.416
A,Z	1	.024	.024	$4\sigma_I^2 + 8\ell\phi(A,Z)$ †	.563
A,H	3	.090	.030	$\sigma_{IH}^2 + 4\ell\phi(A,H)$ ‡	3.156*
C,Z	1	.011	.011	$4\sigma_I^2 + 8\ell\phi(C,Z)$ †	.258
C,H	3	.030	.010	$\sigma_{IH}^2 + 4\ell\phi(C,H)$ ‡	1.052
Z,H	3	.212	.071	$\sigma_{IH}^2 + 4\ell\phi(Z,H)$ ‡	7.470*
3-WAY INTERACTIONS					
A,C,Z	1	.030	.030	$4\sigma_I^2 + 4\ell\phi(A,C,Z)$ †	.704
A,C,H	3	.050	.017	$\sigma_{IH}^2 + 2\ell\phi(A,C,H)$ ‡	1.789
A,Z,H	3	.125	.042	$\sigma_{IH}^2 + 2\ell\phi(A,Z,H)$ ‡	4.419*
C,Z,H	3	.009	.003	$\sigma_{IH}^2 + 2\ell\phi(C,Z,H)$ ‡	.316
4-WAY INTERACTIONS A,C,Z,H	3	.035	.012	$\sigma_{IH}^2 + \ell\phi(A,C,Z,H)$ ‡	1.262
RESIDUALS					
I	98	4.178	.043	$4\sigma_I^2$	
I,H	295	2.804	.010	σ_{IH}^2	
INDEPENDENT VARIABLES	3				
TOTAL	427	9.095			

* SIGNIFICANT AT A 5% LEVEL OF SIGNIFICANCE.

† EXPECTED MEAN SQUARE TERM IS TESTED BY THE TERM (I).

‡ EXPECTED MEAN SQUARE TERM IS TESTED BY THE TERM (IH).

TABLE 10. ANOVA TABLE FOR "PERCENT OF NO CHANCE TO TURN ON RED", MODEL (1)

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	EXPECTED MEAN SQUARES	F
FACTORS					
A	1	.073	.073	$4\sigma_I^2 + 16\ell\phi(A)$ †	2.475
C	1	.024	.024	$4\sigma_I^2 + 16\ell\phi(C)$ †	.814
Z	1	.020	.020	$4\sigma_I^2 + 16\ell\phi(Z)$ †	.678
H	3	.000	.000	$\sigma_{IH}^2 + 8\ell\phi(H)$ ‡	.000
2-WAY INTERACTIONS					
A,C	1	.003	.003	$4\sigma_I^2 + 8\ell\phi(A,C)$ †	.102
A,Z	1	.007	.007	$4\sigma_I^2 + 8\ell\phi(A,Z)$ †	.237
A,H	3	.041	.014	$\sigma_{IH}^2 + 4\ell\phi(A,H)$ ‡	1.952
C,Z	1	.003	.003	$4\sigma_I^2 + 8\ell\phi(C,Z)$ †	.102
C,H	3	.009	.003	$\sigma_{IH}^2 + 4\ell\phi(C,H)$ ‡	.418
Z,H	3	.032	.011	$\sigma_{IH}^2 + 4\ell\phi(Z,H)$ ‡	1.534
3-WAY INTERACTIONS					
A,C,Z	1	.006	.006	$4\sigma_I^2 + 4\ell\phi(A,C,Z)$ †	.203
A,C,H	3	.010	.003	$\sigma_{IH}^2 + 2\ell\phi(A,C,H)$ ‡	.418
A,Z,H	3	.019	.006	$\sigma_{IH}^2 + 2\ell\phi(A,Z,H)$ ‡	.836
C,Z,H	3	.008	.003	$\sigma_{IH}^2 + 2\ell\phi(C,Z,H)$ ‡	.418
4-WAY INTERACTIONS A,C,Z,H	3	.006	.002	$\sigma_{IH}^2 + \ell\phi(A,C,Z,H)$ ‡	.279
RESIDUALS					
I	98	2.890	.029	$4\sigma_I^2$	
I,H	295	2.116	.007	σ_{IH}^2	
INDEPENDENT VARIABLES	3				
TOTAL	427	5.283			

* SIGNIFICANT AT A 5% LEVEL OF SIGNIFICANCE.

† EXPECTED MEAN SQUARE TERM IS TESTED BY THE TERM (I).

‡ EXPECTED MEAN SQUARE TERM IS TESTED BY THE TERM (IH).

2. City size had a significant effect on the percent of vehicles that made a right turn on red. The average RTOR vehicles as a percent of total right turning vehicles was 19.8% in large cities while it was 13.1% in small cities. This result is probably explained by the difference between traffic characteristics in large and small cities. In large cities fast driving is typically greater than in small cities. As a result, the frequency of RTOR maneuvers in large cities is higher than in small cities.
3. Numbers of approach lanes and cross lanes did not have significant effects on vehicles that turned when the traffic signal was red.
4. City size had a significant effect on percent of drivers that refused to turn on red. The reason for that could be explained again by the difference between traffic characteristics in large and small cities. The averages of vehicles refusing to turn on red in large and small cities were 6.5% and 16.3%, respectively, as percentages of total right turning vehicles.
5. The number of approach lanes had a significant effect on the percent of drivers that refused to turn on red. For one-lane approaches the average percent of drivers that refused to turn on red was 11.2% of total right turns, while it was 6.4% for multi-lane approaches. This relationship is shown in Figure 10.
6. The number of cross lanes did not have a significant effect on drivers that refused the opportunity to turn on red.

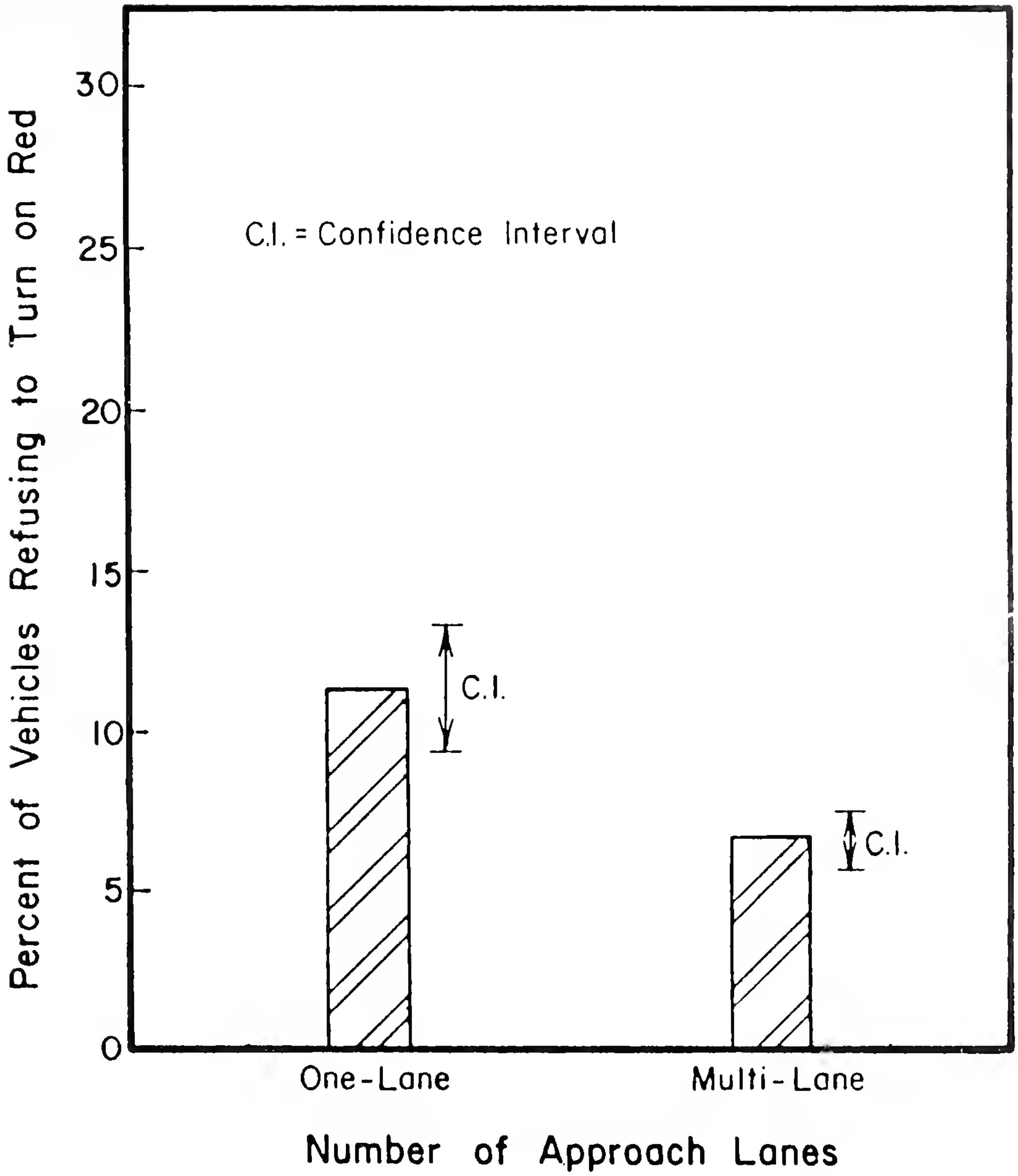

FIGURE 10. EFFECT OF NUMBER OF APPROACH LANES ON PERCENT OF VEHICLES REFUSING TO TURN ON RED

7. The number of approach lanes, the number of cross lanes and city size had no significant effects on the percent of vehicles that did not have the chance to turn on red.

The interactions between hours and other factors that had significant effects in some cases appear to have no reasonable explanation.

Model (2):

One hundred multi-lane approaches were tested in this model. They were divided into eight homogenious cells. Four of these eight cells were used in model (1). The model used was as follows: *

$$Y_{ijk\ell m} - \beta_1 V_{1ijk\ell m} - \beta_2 V_{2ijk\ell m} - \beta_3 R_{ijk\ell m}$$

$$= \mu + S_i + C_j + SC_{ij} + Z_k + SZ_{ik} + CZ_{jk}$$

$$+ SCZ_{ijk} + I_{(ijk)\ell} + \delta_{(ijk\ell)} + H_m + SH_{im} + CH_{jm}$$

$$+ SCH_{ijm} + ZH_{km} + SZH_{ikm} + CZH_{jkm} + SCZH_{ijkm}$$

$$+ IH_{(ijk)\ell m} + \epsilon_{(ijk\ell m)}$$

Where:

$Y_{ijk\ell m}$ = the measured dependent variable, i.e., RTOR vehicles as a percent of total right turns, vehicles that refused the opportunity to turn on red as a percent of total right turns, or vehicles that did not have the chance to turn on red as a percent of total right turns.

μ = overall mean.

S_i = effect of the i^{th} case of a special right turn lane existence.

C_j = effect of the j^{th} class of cross approach lanes.

Z_k = effect of the k^{th} city size.

*For more statistical details see Appendix C.

$I_{(ijk)\ell}$ = effect of the ℓ^{th} approach in the i^{th} case of a special right turn lane existance in the j^{th} class of cross approach lanes in the k^{th} city size.

$\delta_{(ijk\ell)}$ = restriction error, zero df, NID (o,σ_δ^2).

H_m = effect of the m^{th} hour.

$V_{1ijk\ell m}$ = a measure of the approach traffic volume per lane of the i^{th} case of a special right turn lane existance with the j^{th} class of cross lanes with the k^{th} city size with the ℓ^{th} approach with the m^{th} hour.

$V_{2ijk\ell m}$ = a measure of the cross traffic volume per lane of the i^{th} case of a special right turn lane existance with the j^{th} class of cross lanes with the k^{th} city size with the ℓ^{th} approach with the m^{th} hour.

$R_{ijk\ell m}$ = a measure of the red signal time as a percent of total cycle length of the i^{th} case of a special right turn lane existance with the j^{th} class of cross lanes with the k^{th} city size with the ℓ^{th} approach with the m^{th} hour.

β_1, β_2 and β_3 = regression coefficients of V_1, V_2 and R respectively.

$\varepsilon_{(ijk\ell m)}$ = within error, zero df, NID (o, σ^2).

The other terms denote the interactions among the factors S, C, Z, I and H. The subscripts had the following values:

$i = 1, 2$

$j = 1, 2$

$k = 1, 2$

ℓ = variable (number of approaches in each cell)

$m = 1, 2, 3, 4$

The same steps for model (1) were followed again in model (2). Linear regression equations were performed between the different dependent variables and the independent variables V_1, V_2 and R. The linear relationship was proved to be the best fit. The effect of the independent variables was subtracted from the observed values of the dependent variables in order to determine the actual effects of the different factors.

In this model the factors S, C, Z and H are fixed, while the factor I is random. Analysis of variances of RTOR, refused to turn on red, or no chance to turn on red as percentages of total right turning vehicles are shown in Tables 11, 12, and 13 respectively. The different factors were tested at level of significance 5% ($\alpha = .05$).

Studying the different factors that were investigated by the model indicated the following:

1. Hours did not have any effect on the different right turning vehicles because the only differences between different hours were the changes in traffic volumes and signal time which were included in the model.
2. Size of city had a significant effect on the percent of RTOR vehicles. In large cities the average RTOR vehicles as a percent of total right turning vehicles was 21.9%, while it was 17.8% in small cities. This conclusion indicates that the effect of city size was in the same direction in both models.
3. Availability of exclusive right turn lanes had a significant effect on the percent of RTOR vehicles. The average of this percent was 26.3% of total right turning vehicles in case of exclusive right turn lanes, while it was 19.3% in case of non-exclusive right turn lanes. This means that drivers

TABLE II. ANOVA TABLE FOR "PERCENT OF RIGHT TURN ON RED", MODEL (2)

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	EXPECTED MEAN SQUARES		F
FACTORS						
S	1	.227	.227	$4\sigma_I^2 + 16\ell\phi(S)$	†	7.315*
C	1	.027	.027	$4\sigma_I^2 + 16\ell\phi(C)$	†	.870
Z	1	.240	.240	$4\sigma_I^2 + 16\ell\phi(Z)$	†	7.734*
H	3	.000	.000	$\sigma_{IH}^2 + 8\ell\phi(H)$	‡	.000
2-WAY INTERACTIONS						
S,C	1	.012	.012	$4\sigma_I^2 + 8\ell\phi(S,C)$	†	.387
S,Z	1	.028	.028	$4\sigma_I^2 + 8\ell\phi(S,Z)$	†	.902
S,H	3	.016	.005	$\sigma_{IH}^2 + 4\ell\phi(S,H)$	‡	.825
C,Z	1	.008	.008	$4\sigma_I^2 + 8\ell\phi(C,Z)$	†	.258
C,H	3	.038	.013	$\sigma_{IH}^2 + 4\ell\phi(C,H)$	‡	2.146
Z,H	3	.015	.005	$\sigma_{IH}^2 + 4\ell\phi(Z,H)$	‡	.825
3-WAY INTERACTIONS						
S,C,Z	1	.070	.070	$4\sigma_I^2 + 4\ell\phi(S,C,Z)$	†	2.256
S,C,H	3	.007	.002	$\sigma_{IH}^2 + 2\ell\phi(S,C,H)$	‡	.330
S,Z,H	3	.011	.004	$\sigma_{IH}^2 + 2\ell\phi(S,Z,H)$	‡	.660
C,Z,H	3	.025	.008	$\sigma_{IH}^2 + 2\ell\phi(C,Z,H)$	‡	1.320
4-WAY INTERACTIONS S,C,Z,H	3	.029	.010	$\sigma_{IH}^2 + \ell\phi(S,C,Z,H)$	‡	1.651
RESIDUALS						
I	91	2.824	.031	$4\sigma_I^2$		
I,H	274	1.660	.006	σ_{IH}^2		
INDEPENDENT VARIABLES	3					
TOTAL	399	5.197				

* SIGNIFICANT AT A 5% LEVEL OF SIGNIFICANCE.

† EXPECTED MEAN SQUARE TERM IS TESTED BY THE TERM (I).

‡ EXPECTED MEAN SQUARE TERM IS TESTED BY THE TERM (IH).

TABLE 12. ANOVA TABLE FOR "PERCENT OF REFUSED TO TURN ON RED", MODEL (2)

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	EXPECTED MEAN SQUARES	F
FACTORS					
S	1	.000	.000	$4\sigma_I^2 + 16\ell\phi(S)$ †	.000
C	1	.006	.006	$4\sigma_I^2 + 16\ell\phi(C)$ †	.150
Z	1	.209	.209	$4\sigma_I^2 + 16\ell\phi(Z)$ †	5.238*
H	3	.000	.000	$\sigma_{IH}^2 + 8\ell\phi(H)$ ‡	.000
2-WAY INTERACTIONS					
S,C	1	.001	.001	$4\sigma_I^2 + 8\ell\phi(S,C)$ †	.025
S,Z	1	.034	.034	$4\sigma_I^2 + 8\ell\phi(S,Z)$ †	.852
S,H	3	.008	.003	$\sigma_{IH}^2 + 4\ell\phi(S,H)$ ‡	.386
C,Z	1	.006	.006	$4\sigma_I^2 + 8\ell\phi(C,Z)$ †	.150
C,H	3	.022	.007	$\sigma_{IH}^2 + 4\ell\phi(C,H)$ ‡	.901
Z,H	3	.096	.032	$\sigma_{IH}^2 + 4\ell\phi(Z,H)$ ‡	4.118*
3-WAY INTERACTIONS					
S,C,Z	1	.046	.046	$4\sigma_I^2 + 4\ell\phi(S,C,Z)$ †	1.153
S,C,H	3	.015	.005	$\sigma_{IH}^2 + 2\ell\phi(S,C,H)$ ‡	.643
S,Z,H	3	.043	.014	$\sigma_{IH}^2 + 2\ell\phi(S,Z,H)$ ‡	1.802
C,Z,H	3	.021	.007	$\sigma_{IH}^2 + 2\ell\phi(C,Z,H)$ ‡	.901
4-WAY INTERACTIONS S,C,Z,H	3	.077	.026	$\sigma_{IH}^2 + \ell\phi(S,C,Z,H)$ ‡	3.346*
RESIDUALS					
I	91	3.631	.040	$4\sigma_I^2$	
I,H	274	2.129	.008	σ_{IH}^2	
INDEPENDENT VARIABLES	3				
TOTAL	399	6.365			

* SIGNIFICANT AT A 5% LEVEL OF SIGNIFICANCE.

† EXPECTED MEAN SQUARE TERM IS TESTED BY THE TERM (I).

‡ EXPECTED MEAN SQUARE TERM IS TESTED BY THE TERM (IH).

TABLE 13. ANOVA TABLE FOR "PERCENT OF NO CHANCE TO TURN ON RED", MODEL (2)

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	EXPECTED MEAN SQUARES	F
FACTORS					
S	1	.451	.451	$4\sigma_I^2 + 16\ell\phi(S)$ †	15.481*
C	1	.000	.000	$4\sigma_I^2 + 16\ell\phi(C)$ †	.000
Z	1	.019	.019	$4\sigma_I^2 + 16\ell\phi(Z)$ †	.652
H	3	.000	.000	$\sigma_{IH}^2 + 8\ell\phi(H)$ ‡	.000
2-WAY INTERACTIONS					
S,C	1	.001	.001	$4\sigma_I^2 + 8\ell\phi(S,C)$ †	.034
S,Z	1	.000	.000	$4\sigma_I^2 + 8\ell\phi(S,Z)$ †	.000
S,H	3	.010	.003	$\sigma_{IH}^2 + 4\ell\phi(S,H)$ ‡	.527
C,Z	1	.001	.001	$4\sigma_I^2 + 8\ell\phi(C,Z)$ †	.034
C,H	3	.003	.001	$\sigma_{IH}^2 + 4\ell\phi(C,H)$ ‡	.176
Z,H	3	.011	.004	$\sigma_{IH}^2 + 4\ell\phi(Z,H)$ ‡	.703
3-WAY INTERACTIONS					
S,C,Z	1	.001	.001	$4\sigma_I^2 + 4\ell\phi(S,C,Z)$ †	.034
S,C,H	3	.011	.004	$\sigma_{IH}^2 + 2\ell\phi(S,C,H)$ ‡	.704
S,Z,H	3	.033	.011	$\sigma_{IH}^2 + 2\ell\phi(S,Z,H)$ ‡	1.933
C,Z,H	3	.006	.002	$\sigma_{IH}^2 + 2\ell\phi(C,Z,H)$ ‡	.352
4-WAY INTERACTIONS S,C,Z,H	3	.003	.001	$\sigma_{IH}^2 + \ell\phi(S,C,Z,H)$ ‡	.176
RESIDUALS					
I	91	2.651	.029	$4\sigma_I^2$	
I,H	274	1.559	.006	σ_{IH}^2	
INDEPENDENT VARIABLES	3				
TOTAL	399	4.760			

* SIGNIFICANT AT A 5% LEVEL OF SIGNIFICANCE

† EXPECTED MEAN SQUARE TERM IS TESTED BY THE TERM (I).

‡ EXPECTED MEAN SQUARE TERM IS TESTED BY THE TERM (IH).

have more chances to turn on red when there is a special right turn lane on the approach. Figure 11 shows the effect of the special right turn lane on RTOR performance.

4. The percent of RTOR vehicles was not affected significantly by number of lanes in the cross approach.
5. City size had a significant effect on vehicles that refused to turn on red. The averages in large and small cities were 6.3% and 12.8% respectively, as percentages of total right turning vehicles. This result agrees with model (1).
6. Availability of a right turn lane only had no effect on vehicles that refused the opportunity to turn on red.
7. The number of lanes in the cross direction did not have a significant effect on vehicles that refused to turn on red.
8. The percent of vehicles that did not have opportunities to turn on red was affected significantly by the availability of a special right turn lane. Vehicles that did not have the chance to turn on red as a percent of total right turns had an average of 11.2% when a special right turn lane was available, while this percentage was 22.0% when there was no special right turn lane. Figure 12 indicates this result.
9. The number of cross lanes and city size did not have significant influences on the percent of vehicles that did not have the chance to turn on red.

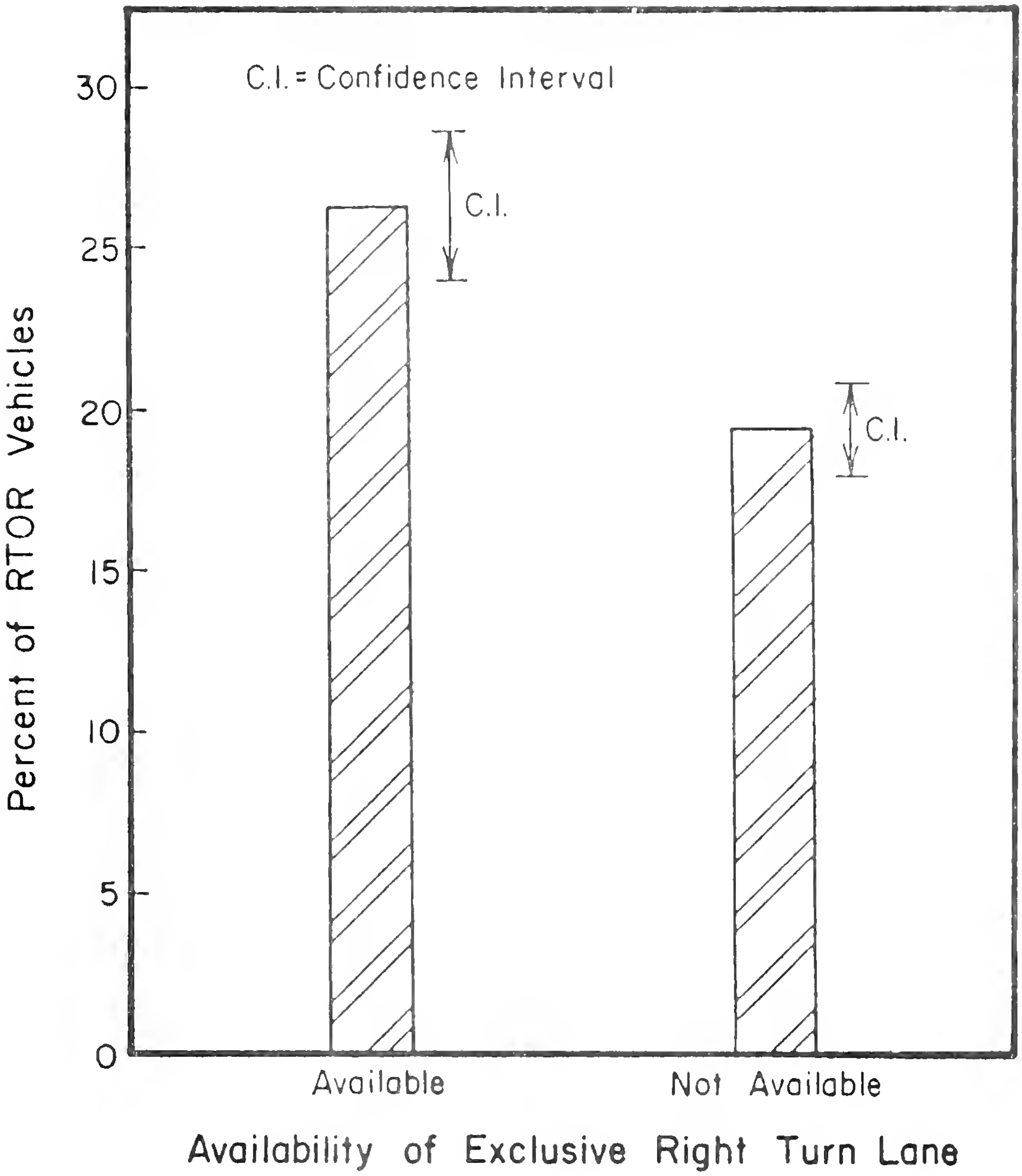

FIGURE 11. EFFECT OF EXCLUSIVE RIGHT TURN LANE ON PERCENT OF RTOR VEHICLES

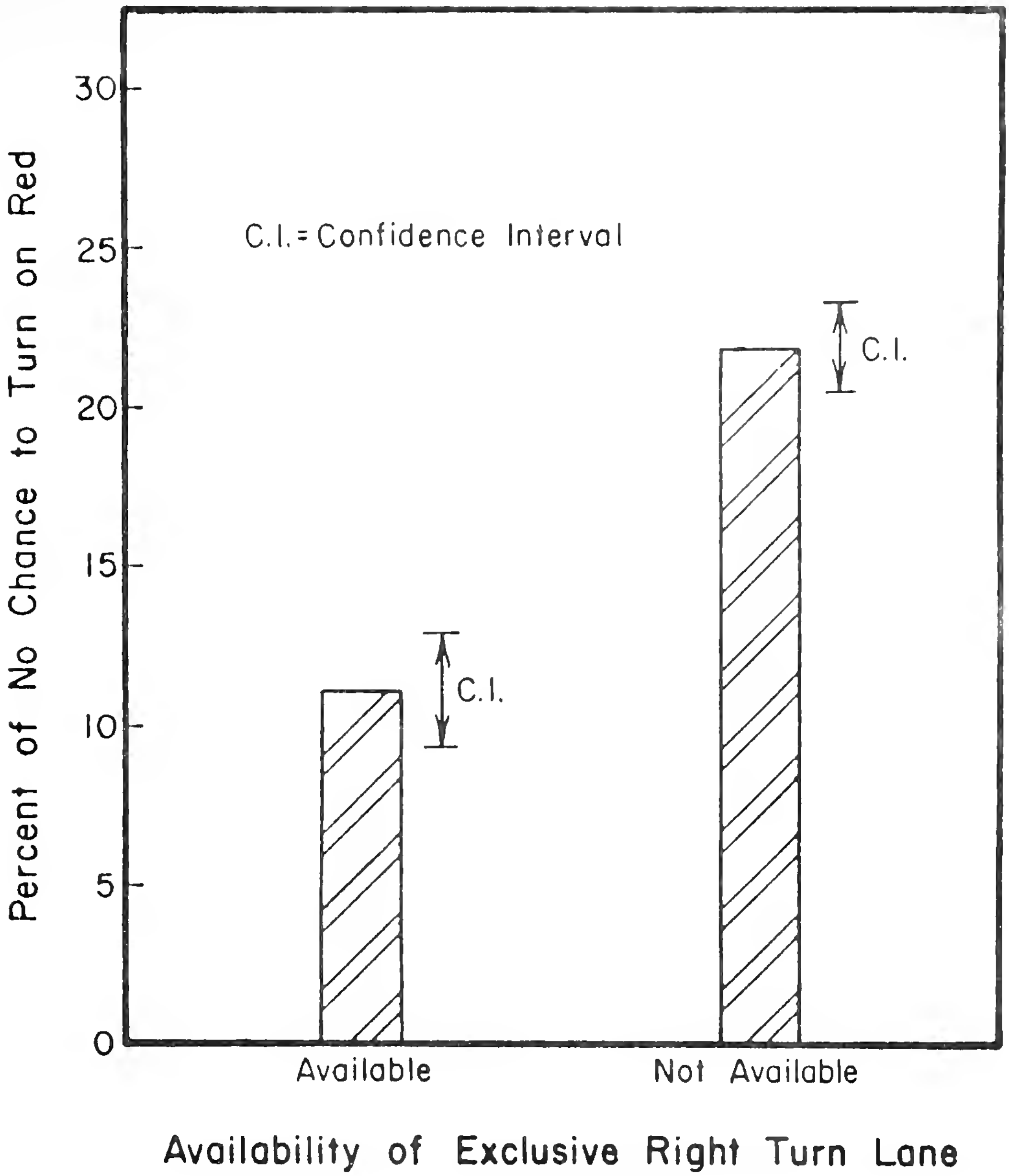

FIGURE 12. EFFECT OF EXCLUSIVE RIGHT TURN LANE ON PERCENT OF NO CHANCE TO TURN ON RED

An overall analysis of results of the two models shows that the common factors had the same effects in both models. City size had the same effect on vehicles that made a right turn on red in both models. Using the data of all non-progressive signal approaches, it is seen that average of RTOR vehicles as a percent of total right turns dropped from 21.3% in large cities to 15.6% in small cities as shown in Figure 13.

Size of city also gave the same effect on vehicles that refused to turn on red in both models. In large cities percent of vehicles that refused to turn on red was 6.7%, while in small cities it was 15.5% as a percent of total right turning vehicles. This result is shown in Figure 14.

Effect of Independent Variables

The aim was to determine the effect of traffic approach volume, cross traffic volume, and signal time on the performance of right turning vehicles. The dependent variables that were considered in the study were: RTOR vehicles, vehicles that refused to turn on red, and vehicles that did not have the chance to turn on red as percentages of total right turning vehicles.

Due to the complexity of the problem and the different factors that were involved, it was decided to determine the effect of the independent variables without including the different factors in the model. This solution was considered to be acceptable for the purpose of this study.

Using the total data that were collected from the one hundred and fifty approaches, regression equations were performed between the different combinations of the dependent and independent variables. The regression model was applied separately to each one of the four observation hours. The model that was considered for each dependent variable and for each observation hour was as follows:

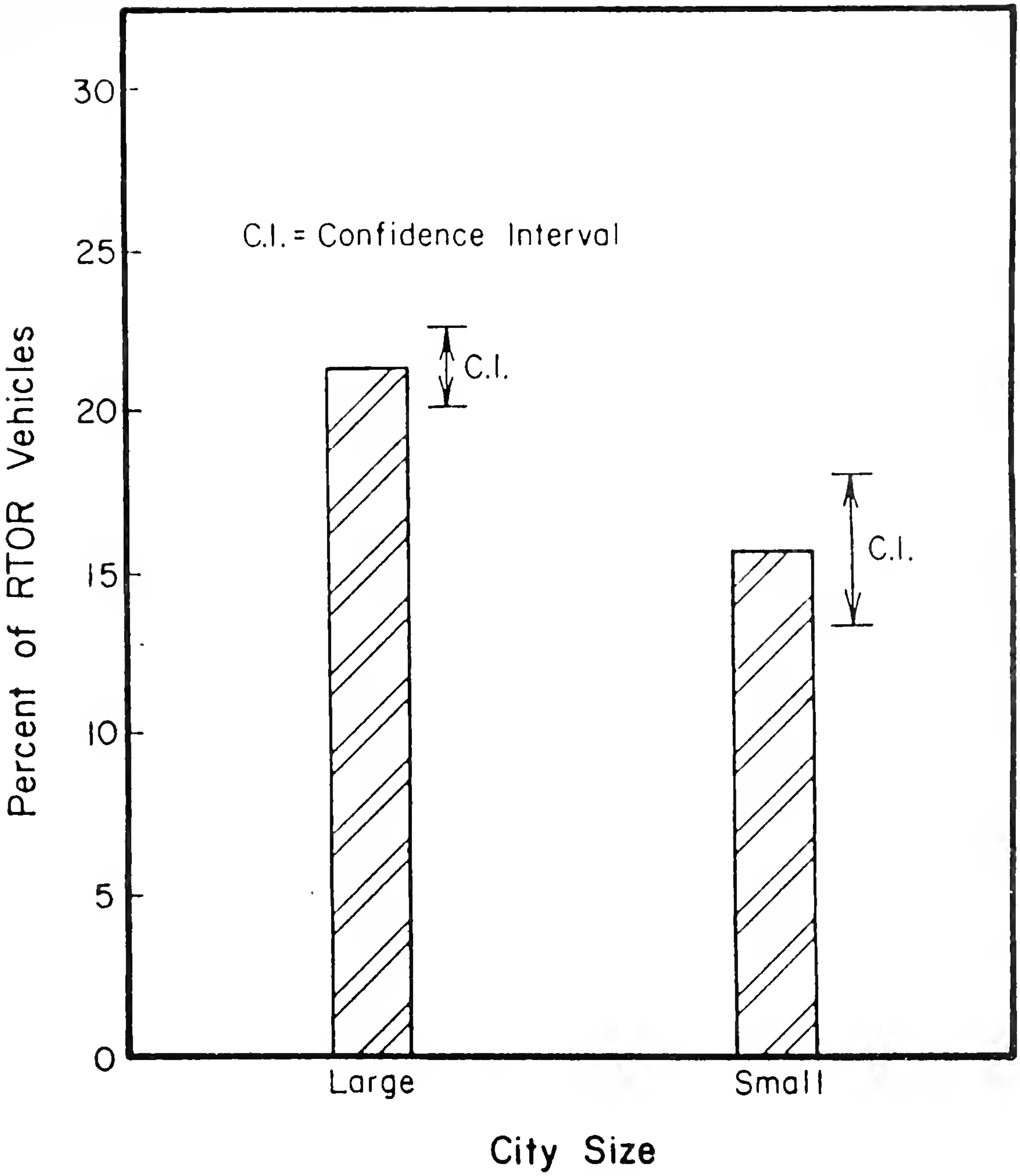

FIGURE 13. EFFECT OF CITY SIZE ON PERCENT OF ROTR VEHICLES

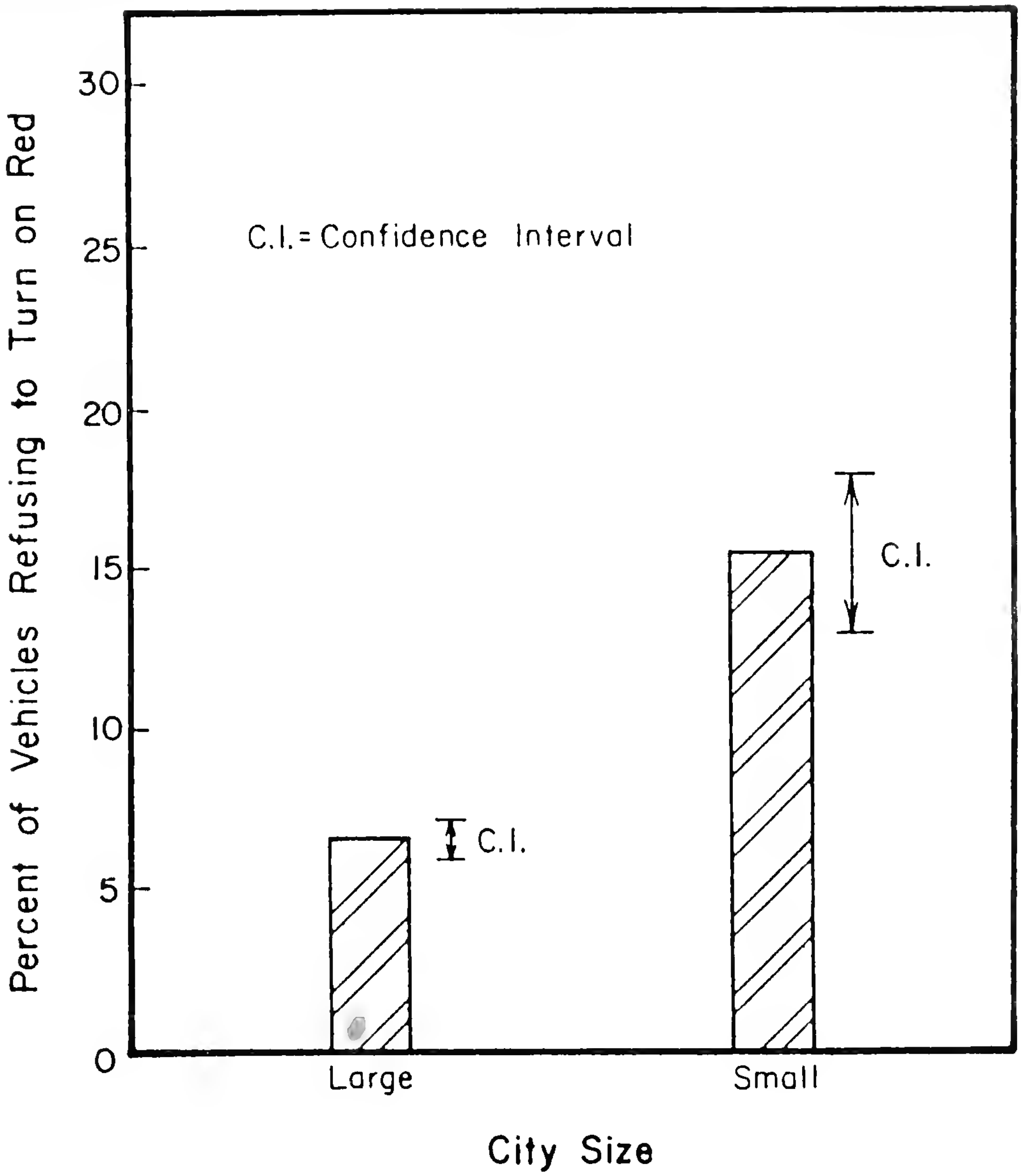

FIGURE 14. EFFECT OF CITY SIZE ON PERCENT OF VEHICLES REFUSING TO TURN ON RED

$$Y_i = \beta_0 + \beta_1 V_{1i} + \beta_2 V_{2i} + \beta_3 R_i + \varepsilon_{(i)}$$

Where:

Y_i = the measured dependent variable, i.e., RTOR as a percent of total right turning vehicles; vehicles that refused to turn on red as a percent of total right turning vehicles; or vehicles that did not have the chance to turn on red as a percent of total right turning vehicles.

V_{1i} = effect of the traffic volume per lane of the i^{th} approach.

V_{2i} = effect of the cross traffic volume per lane of the i^{th} approach.

R_i = effect of the red signal time as a percent of the total cycle length of the i^{th} approach.

$\beta_0, \beta_1, \beta_2$ and β_3 = regression coefficients.

$\varepsilon_{(i)}$ = within error, zero df, NID (o, σ^2).

The subscript had the following values:

$i = 1, 2, \ldots, 600$

Normality, additivity and independence of errors were assumed.

Tests for significance of the different variables were performed at a 5% level of significance. F values that were calculated from these tests for each observation hour are shown in Table 14. The overall significance in the Table was concluded according to the significance of each observation hour. Correlation signs were found to be the same for the four observation hours for each variable combination. $F_{critical}$ at 5% level of significance is 3.89. Significant and non-significant effects are denoted by the letters "S" and "NS", respectively.

TABLE 14. F-VALUES FOR THE DIFFERENT VARIABLES FOR THE FOUR OBSERVATION HOURS

Dependent Variables	Independent Variables	Observation Hour				Overall Significance	Correlation
		1	2	3	4		
Percent of RTOR	Approach volume per lane	3.38	8.21*	4.93*	4.84*	S	-ve
	Cross volume per lane	8.54*	13.91*	7.70*	7.72*	S	-ve
	Percent of red signal	19.54*	9.56*	4.18*	9.23*	S	+ve
Percent of Refused to turn on red	Approach volume per lane	7.08*	6.82*	1.47*	6.32*	S	-ve
	Cross volume per lane	2.93	7.31*	.14	.42	NS	+ve
	Percent of red signal	.04	.07	2.13	.13	NS	+ve
Percent of no chance to turn on red	Approach volume per lane	5.46*	9.42*	3.64	20.16*	S	+ve
	Cross volume per lane	11.50*	11.15*	6.40*	3.15	S	+ve
	Percent of red signal	.32	2.28	7.94*	8.34*	doutful	+ve

* Significant at 5% level of signficance.

From Table 14 the following results were concluded:

1. As the approach volume per lane decreased, percent of vehicles that turned on red increased. The reason for this is that the potential for turning vehicles to be obstructed by the through traffic during the red signal phase is greater for higher approach volumes.
2. As traffic volume in the cross direction per lane decreased, the percent of vehicles that turned on red increased. The reason for this is that for low cross traffic volume the length of gaps will be greater in such a way as to permit more RTOR maneuvers.
3. Signal phase time split had a significant effect on RTOR vehicles. The higher the percent of red phase signal, the more RTOR movements. This can be explained by the increase of the percent of vehicles that arrive on red when the percent of red is higher.
4. The lower the approach traffic volume per lane, the higher the percent of vehicles that refused to turn on red.
5. There was no statistically significant effect for cross traffic volume on the percent of vehicles that refused to turn on red when they had the chance to do so. However, the increase of the cross traffic flow caused an increase of the percent of drivers that refused to turn on red. This could be attributed to the lack of confidence of drivers to turn on red when the cross traffic flow is high.
6. The percent of red signal time did not have a significant effect on the percent of vehicles that refused to turn on red.

7. Approach volume had a significant effect on the chances to turn on red. The lower the approach traffic volume, the higher the chances to turn on red. This again is explained by the increase in the probability of turning vehicles to be free to turn on red for lower approach volumes.
8. The increase of cross traffic volume increased the percent of vehicles that did not have the chance to turn on red. In other words, the increase of the flow of vehicles in the cross direction approach decreased the chances for turning vehicles to turn on red. This is explained by the decrease in the number of gaps which were adequate for turning vehicles.
9. No accurate results could be obtained regarding the relationship between the percent of vehicles that did not have the chance to turn on red and signal phase time. Tests indicated that there was no significant effect in the morning off-peak hours and that there was a significant effect in the afternoon peak hours. This might be attributed to the different factors that were neglected in this model.

Traffic Conflict

According to the field study of the accident potential of vehicles that turned on red into the path of through vehicles, it was observed that the number of conflicts was very low in most cases. The number of brakelights or lane changes that was observed in the through traffic to avoid collision with right-turning vehicles did not exceed one or two per hour. In most cases there were no brakelights or lane changes observed at all while the number of RTOR vehicles was reasonably high. Moreover, no severe braking occurred in any one of the observed conflicts.

Although many vehicles that turned on red did not come to a complete stop before turning, the number of conflicts was not increased. This means that most of the drivers that turned on red while facing the red signal were careful relative to approach traffic on the cross street.

The number of conflicts was observed to be higher when the traffic volume in the cross direction was high and fast. However, the number of conflicts was very small and, hence, no significant results could be ascertained. Also, it was observed that the number of conflicts was higher when the sight distance was not adequate to make the RTOR movement.

Although the difference was not significant, the number of conflicts in large cities was higher than in small cities. This might be attributed to the low percentages of RTOR occurrence and the slow movement of traffic in small cities.

As a result, the RTOR movement did not cause a significant increase in the accident potential of the intersection. Although not evaluated, RTOR might actually decrease certain types of traffic conflicts by clearing the intersection and expediting traffic movement.

Pedestrians

During the data collection periods, RTOR vehicles did not cause any significant problems to pedestrians at the studied intersections. In most cases motorists yielded the right of way to the pedestrians before turning.

No pedestrian delays were observed during most of the study period resulting from a RTOR maneuver. In some cases, if a pedestrian had arrived before the vehicle completed the turn, the pedestrian had either to wait for the vehicle to move or to walk out of the crosswalk and around the vehicle. However, this case was very infrequent, especially when pedestrian volume was low.

No pedestrian was observed who had been placed in a more hazardous situation caused by a RTOR maneuver in all the studied intersections over the 600 hours of study. In general, percent of RTOR vehicles was so small that no significant conflict occurred between pedestrians and right turning vehicles.

Although RTOR vehicles may be in conflict with some pedestrians crossing the approach, it should be noted that when vehicles turn on green they will be in conflict with a substantial percentage of the pedestrians in the cross street. As a result, pedestrian conflict with vehicles is not increased by the RTOR maneuver as compared to RTOG.

Driver Irritation

When a driver desires the vehicle in front of him to perform a RTOR maneuver he may sound his horn as an indication for his irritation. Although the sounding of horns is not the only sign of driver irritation, it was the only possible indication that could be measured in this study.

During the 600 observation hours of the right turn on red maneuver the number of horns that were sounded as an indication of driver irritation did not exceed six. As a result, very little driver irritation could be attributed to the turn on red maneuver.

On the other hand, the RTOR movement reduces driver irritation by preventing unnecessary delays. As a matter of fact, many drivers probably prefer to turn on red rather than be compelled to wait for the green signal.

2. Left Turn on Red

In an attempt to learn the extent the left-turn-on-red maneuver was performed, a careful analysis was conducted of the available data. Means and standard deviations of the

different left-turn vehicle groups are summarized as follows:

	Mean	Standard Deviation
% LTOR vehicles (stopped before turning)	1.3	0.0
% LTOR vehicles (did not stop before turning)	0.0	0.0
% Vehicles that refused to turn on red	19.6	18.7
% Vehicles that did not have the chance to turn on red	15.9	11.4
% Vehicles that arrived and turned on green	63.2	21.2

The means and standard deviations were calculated as percentages of the total left-turn vehicles.

If one compares between LTOR and RTOR results, it can be concluded that the LTOR vehicles were a very low percent relative to RTOR vehicles. Percent of LTOR vehicles ranged from a low of zero percent to a high of 10 percent. Also, the percent of drivers that refused the opportunity to make a left-turn-on-red was higher than percent of drivers that refused the opportunity to make a right-turn-on-red.

If the total left rurn vehicles were about 20% of the total approach traffic volume, the LTOR vehicles were only 0.26 of 1% of the total approach volume which is an insignificant value. As a conclusion, the drivers in Indiana have not yet become acquainted with the LTOR maneuver as is the case for the RTOR maneuver.

During the data collection periods all drivers that made the LTOR maneuver came to a full stop or a rolling stop before turning. No traffic conflicts between LTOR vehicles and vehicles approaching from the right were recorded during the study period. Because of the very small

LTOR, this movement had a very small probability of increasing the accident potential at signalized intersections.

An attempt was made to study the effect of the different intersection characteristics and traffic volumes on the LTOR maneuver. However, accurate results could not be obtained because of the infrequency of the maneuver.

Dealing with pedestrian conflicts with the maneuver, it was observed that vehicles that made a left turn against the red signal yielded to pedestrians before turning. No pedestrian delay of any kind was recorded due to the maneuver. Moreover, no pedestrian was observed to be put in a hazardous situation because of a LTOR movement.

As for driver irritations, no horns were recorded as an indication to drivers desiring the vehicles in front of them to make a LTOR movement. Probably this result could be attributed to the small number of drivers that intended to make LTOR in general.

From the previous analysis, it is concluded that permitting the LTOR maneuver from a one-way street to a one-way street as a basic rule in Indiana has not yet achieved its purpose. No problems resulting from the maneuver could be observed during the study periods. Educational programs may be needed to encourage drivers to perform the maneuver when it is safe to do so.

3. Turn on Red Prohibition

According to the field survey at the approaches where the RTOR maneuver was prohibited, the number of violations ranged from zero to four per hour. Percentages of violations ranged from a low of zero percent to a high of 10 percent of the total right turning vehicles. The average percent of violations was 1.4 percent of the total vehicles that made a right turn.

During the study, an exceptional location was observed where percent of violations was 18% as a percent of total right turning vehicles. In this special case the high number of violations could be attributed to the very bad location of the NO TURN ON RED sign which was confusing to the motorists and was hard to see.

Number of turn-on-red prohibition signs varied widely from one city to another in Indiana depending on the different characteristics of the intersection approaches. The reasons for turn-on-red prohibitions varied also from one city to another*.

The number of violations depends on the intersection characteristics as well as the drivers characteristics. An attempt was made to determine the different factors that affected the number of violations. It was concluded that the number of violations increased when the approach traffic was heavy and the crossing traffic was light. However, no significant results were ascertained.

Also, it was observed that the number of violations was affected by the types of vehicle. Percent of motorcycles that turned on red where the maneuver was prohibited was more than percent of other vehicles. No RTOR violations were observed to be made by trucks at the studied loations.

City size had no significant effect on number of RTOR violations. However, the number of violations observed seemed to be higher in large cities than in small cities.

A study was performed to determine the effect of NO TURN ON RED sign location on percent of violations. A high percent of RTOR prohibition signs was post mounted at the corners of the intersections, while the signal was overhead mounted. This situation could make the sign unnoticed. According to the data, however, no significant difference in percent of RTOR violations was observed

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*For more information for the RTOR prohibition reasons refer to the questionnaire in Chapter 5.

between the locations where the sign was overhead mounted or post mounted.

In some cities where the survey was conducted it was noticed that the NO TURN ON RED sign was followed by the statement: when pedestrians are present. According to Indiana traffic practice, it is not desirable to prohibit the RTOR movement for specific times of the day or for special classifications or conditions. However, from the data that were collected, the number of signs of this type was very low.

The left-turn-on-red prohibition from a one-way street to a one-way street was working very efficiently. Although the number of observations was small, no violations were recorded at the studied locations.

At some few locations the turn-on-red was allowed where it should be prohibited. Also, at some other locations the maneuver was prohibited without a clear reason for this prohibition. Careful study is needed to determine the exact locations where the maneuver should be allowed or prohibited. In general, it is concluded that the turn-on-red prohibition is working fairly well and that drivers comply very well with the regulations.

CHAPTER 5. QUESTIONNAIRE ON RTOR

As was expected, some traffic authorities in Indiana were not enthusiastic supporters of the RTOR maneuver and some feared that the effect on accidents, pedestrians or driver irritation would be substantial. One phase of this study, therefore, included contact with the traffic officials in the state of Indiana to evaluate their appraisal after one year of the quality of use of this maneuver in the different cities.

In July, 1975, a questionnaire was sent to the traffic engineers, traffic officers or chiefs of police in 111 cities in Indiana to obtain information regarding their use of and experience with the RTOR maneuver. Replies were received from 74 cities distributed throughout the state representing 67% of total cities*.

Traffic officials in some larger communities in Indiana were interviewed to determine their utilization, including warrants used, of RTOR.

Some of the answers received gave adequate information about the practice of the maneuver while others were incomplete. However, a general idea about how RTOR was working in Indiana was obtained. Comments of the traffic officials made on the questionnaire or in interviews were helpful in identifying the benefits that were being gained from the maneuver and the problems resulting from it.

The first question in the questionnaire sought information about the number of signalized intersections. The second question, attempted to determine the number of typical 4-way signalized intersections so that an evaluation

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*For sample questionnaire and list of cities replying see Appendix B.

might be made of the relationship between the regularity of the intersections and RTOR practice. From the third and fourth questions, the percentage of signalized intersection approaches where RTOR was prohibited was determined.

A list of reasons for RTOR prohibition was given in the fifth question. The respondent was asked to write the frequency of approaches at which the maneuver was prohibited for each reason.

In the sixth question information about two matters, the effect of the RTOR on accidents and the incidence of problem locations where the maneuver is or had been permitted, was requested.

The data obtained from the questionnaire were tested for completeness and accuracy. About 75% of the answers provided adequate information while the rest were not usable. In tabulating answers, the cities of Indiana were divided into two major groups, large and small cities.

The analysis of answers to the third and fourth questions indicated that the percentage of signalized intersection approaches where the RTOR was prohibited to the total number of signalized intersection approaches varied widely from one city to another. This percentage ranged from zero percent in some small cities to 83.1 percent in other cities as shown in the listing below:

Percent of Approaches at which RTOR was Prohibited

	Maximum	Minimum	Average
Large cities	28.8	1	10.9
Small cities	83.1	0	12.5

The average percentage of signalized intersection approaches at which the maneuver was prohibited was 12.0% of the total signalized approaches. It was concluded that the RTOR maneuver had been allowed at about 88% of the total signalized intersection approaches in Indiana,

certainly a significant percentage. It also was concluded that utilization of the RTOR is approximately the same in both large and small cities.

In the fifth question the listed reasons for RTOR prohibition were:

1. Inadequate sight distance.
2. The intersection has more than four approaches.
3. A separate signal phase for a turning movement exists at the intersection which would conflict with a RTOR movement.
4. There is very short red time for the approach.
5. Cross street traffic is heavy.
6. School crossing at the intersection.
7. Other pedestrian crossing is heavy.
8. Little right turn demand exists.
9. Others.

When the answers to this question were analyzed, the average percents of the frequencies of each reason and the ranges for both large and small cities were as shown in Table 15.

From this Table it is clear that both inadequacy of sight distance and a conflicting separate signal phase were the most frequent reasons for RTOR prohibition, while little right turn demand was the least important.

Concerning accidents as obtained from question 6, it was found that twenty accidents were attributed to RTOR movements during the past year by the questionnaire respondents. Eighteen of these accidents occurred in large cities while only two accidents were reported from small cities. All these accidents involved only minor property damages or minor injuries. No fatalities or serious injuries were reported in responses on the questionnaire. Most accidents were reported to have been caused by vehicles which did not come to a full stop before turning and proceeded into the intersection without yielding the right-of-way

Table 15. Frequencies of Reasons for RTOR Prohibition (in percent)

Reason Number	Average			Range	
	Large Cities	Small Cities	All Cities	Maximum	Minimum
1	27.6	32.2	28.5	100.0	0.0
2	9.5	4.1	8.5	55.5	0.0
3	29.2	22.6	27.9	100.0	0.0
4	0.7	0.0	0.5	5.0	0.0
5	5.3	15.1	7.2	100.0	0.0
6	6.2	9.6	6.9	100.0	0.0
7	14.8	10.9	14.0	44.4	0.0
8	0.0	0.7	0.1	25.0	0.0
9	6.7	4.8	6.4	100.0	0.0

to the cross traffic. Only two of these accidents were classified as pedestrian accidents. They were reported in large cities during peak hours. These two accidents occurred due to the drivers' failure to come to a complete stop before turning.

From the interviews that were made with traffic officials in some Indiana cities, and from analyzing the comments that were reported in the questionnaire, it was concluded that most traffic officials were in favor of allowing the right-turn-on-red maneuver. Although some problems were reported, the general opinion was that the RTOR was working reasonably well.

The following were among the comments and problems that were reported in the answers to the questionnaire received from traffic engineers in large cities:

> "The only problem we find with the Right Turn on Red is that the motorist making the turn does not stop before making the turn and has had several near accident misses."

> "We have not had any problems with RTOR and have observed an increase in traffic volume especially at those intersections where we have an exclusive right turn lane."

> "In some intersections, drivers do not stop before turning as a habit...RTOR needs good enforcement..."

> "Most people favor the right turn on red."

> "The RTOR system has worked well since the one year inception. Basically the only problem is that drivers do not understand the severity of the situation and too often proceed to turn right on red without coming to a complete stop."

> "I am very much in favor of RTOR but I feel that all states must handle it in the same way."

Comments received from traffic officials and police officers in small towns were also very much in favor of allowing the right-turn-on-red.

The following were some of the comments received:

> "I feel this is a good law and of great benefit to the drivers. This is especially true in a small town where there is not much traffic..."

> "I believe that this should have been done several years ago. It has improved the movement of traffic and has not yet caused any problems."

> "A large portion of the traffic does not utilize the right turn on red law."

> "People are abusing one right of the new law, they are not stopping before turning..."

> "...I think it will work well in towns that have streets that can handle certain volumes of traffic and have gaps in the flow."

As an overall impression from these comments, it was concluded that large cities have more problems with the RTOR than small cities. This perhaps should have been expected due to the higher speeds of vehicles and the larger volume of traffic in large cities. The slower traffic movement in small cities reduces the conflicts that might result from the RTOR maneuver. Moreover, more motorists in small cities refuse to turn on red when they have the chance to do so.

Most traffic officials in Indiana were in favor of allowing the right-turn-on-red as a basic rule because it tends to decrease the delay and increase the volume served at signalized intersections. The only problem reported was that some drivers do not come to a full stop before turning. As a result, some conflicts do occur with the cross traffic which has the right of way.

Some RTOR vehicles were involved in some accidents, but the severity of these accidents was not significant. Moreover, some of these reported accidents could be attributed to the poor design of the intersection or the

practice of allowing RTOR at locations where it should be prohibited for one reason or another.

CHAPTER 6. FINDINGS AND CONCLUSIONS

According to the data collected in this study, certain conclusions were obtained regarding the practice of right-turn-on-red after almost one year of allowing the maneuver as a basic rule in Indiana. These conclusions and findings are:

1. The RTOR maneuver is made by only 19.5% of the total right turning vehicles and 3.7% of the total approach volume.
2. Although the difference was not statistically significant, the use of a progressive signal system decreased the percent of RTOR vehicles.
3. City size had a significant effect on the percent of RTOR vehicles. This percent was 21.3% in large cities while it was 15.6% in small cities as a percent of total right turning vehicles.
4. Availability of an exclusive right turn lane increased percent of RTOR vehicles significantly. When there was no special right turn lane percent of RTOR vehicles was 19.3% of total right turning vehicles, while it was 26.3% where there was a special right turn lane.
5. The number of approach lanes and the number of cross lanes did not have a significant effect on the percent of RTOR vehicles.
6. City size had a significant effect on percent of vehicles that refused the opportunity to turn on red. In large cities this percent was 6.7 while it was 15.5 in small cities as a percent of total right turning vehicles.

7. The number of approach lanes had an effect on the percent of vehicles that refused to make a RTOR, from 11.2% in case of one-lane approaches to 6.4% in case of multi-lane approaches as a percent of total right turning vehicles.
8. Availability of an exclusive right turn lane and the number of lanes approaching from the left did not have a significant effect on vehicles which refused to make the RTOR maneuver.
9. Availability of a special right turn lane increased the vehicles' chances to turn on red significantly.
10. The number of approach lanes, the number of cross lanes and the size of the city did not have significant effects on a vehicles' chance to turn on red.
11. Percent of RTOR vehicles increased significantly with a decrease of the approach traffic volume and also with a decrease of the cross traffic volume.
12. Percent of vehicles that refused to make a RTOR increased significantly with a decrease of the approach traffic volume.
13. Although no statistically significant result was indicated, the percent of vehicles that refused to make a RTOR was increased with an increase of the cross traffic volume.
14. Percent of vehicles that did not have the chance to make the RTOR maneuver increased significantly with an increase of the approach traffic volume and with an increase of the cross traffic volume.

15. An increase in percent of red signal time increased percent of vehicles that made a RTOR. It did not have a significant effect on percent of vehicles that refused to turn on red or vehicles that did not have the chance to turn on red.
16. The LTOR maneuver was used by only 1.3% of the total left turning vehicles and 0.26 of 1% of the total approach volume.
17. The percent of vehicles that made a RTOR at locations where the maneuver was prohibited was 1.4% of the total right turning vehicles.
18. The number of traffic conflicts between RTOR vehicles and the cross traffic was very small and did not cause any significant problem.
19. The turn-on-red maneuver did not result in hazard to pedestrians crossing the intersection. Most drivers that turned on red yielded the right-of-way to the pedestrians.
20. Although some vehicles did not come to a full stop before turning on red, they did not represent any real problem to the performance of the maneuver. A very small number of vehicles were observed to turn on red without stopping or slowing down before turning.
21. According to answers to a questionnaire that were received from the traffic officials in cities of Indiana, the RTOR maneuver was working efficiently. Most of the traffic officials were in favor of allowing the maneuver. Twenty RTOR accidents were reported in the questionnaire, however, they involved only minor property damages or minor injuries.

22. Driver education programs appear to be needed to encourage drivers to turn on red when it is safe to do so. Also, more enforcement may be needed to force drivers to come to a full stop before turning.

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APPENDICES

APPENDIX A

Locations From Which the Data were Collected

Table A-1. Cities, Intersections and Approaches from which the Data of RTOR were Collected

1. Anderson

Intersection	Approach
Madison Ave. & 38th St.	Madison Ave. (NB)
Madison Ave. & 38th St.	Madison Ave. (SB)
Madison Ave. & 38th St.	38th St. (EB)
Madison Ave. & 38th St.	38th St. (WB)
Madison Ave. & 53rd St.	Madison Ave. (NB)
Madison Ave. & 53rd St.	Madison Ave. (SB)
Madison Ave. & 53rd St.	53rd St. (EB)
Madison Ave. & 53rd St.	53rd St. (WB)
Pendleton Ave. & 38th St.	Pendleton Ave. (NB)
Pendleton Ave. & 38th St.	38th St. (EB)

2. Bloomington

Intersection	Approach
College Ave. & 4th St.	College Ave. (SB)
College Ave. & 4th St.	4th St. (EB)
Walnut St. & 7th St.	Walnut St. (NB)
Walnut St. & 7th St.	7th St. (WB)

3. Columbus

Intersection	Approach
Brown St. & 3rd St.	3rd St. (WB)
Brown St. & 8th St.	Brown St. (NB)
Franklin St. & 3rd St.	3rd St. (WB)
Lindsey St. & 8th St.	8th St. (EB)

4. Evansville

Intersection	Approach
Franklin St. & St. Joseph Ave.	St. Joseph Ave. (NB)
Franklin St. & St. Joseph Ave.	St. Joseph Ave. (SB)
Franklin St. & St. Joseph Ave.	Franklin St. (EB)
Franklin St. & St. Joseph Ave.	Franklin St. (WB)
Virginia St. & Heidelbach Ave.	Heidelbach Ave. (NB)
Virginia St. & Heidelbach Ave.	Heidelbach Ave. (SB)
Virginia St. & Heidelbach Ave.	Virginia St. (EB)
Virginia St. & Heidelbach Ave.	Virginia St. (WB)

5. Fort Wayne

Intersection	Approach
Anthony Blvd. & Pettit Ave.	Anthony Blvd. (NB)
Anthony Blvd. & Pettit Ave.	Anthony Blvd. (SB)
Anthony Blvd. & Pettit Ave.	Pettit Ave. (EB)
Anthony Blvd. & Pettit Ave.	Pettit Ave. (WB)
Jefferson St. & Fairfield St.	Jefferson St. (EB)
Jefferson St. & Ewing St.	Ewing St. (NB)
Main St. & Van Buren St.	Van Buren St. (NB)
Main St. & Van Buren St.	Van Buren St. (SB)
Main St. & Van Buren St.	Main St. (EB)
Main St. & Van Buren St.	Main St. (WB)
State Blvd. & Wells St.	Wells St. (NB)
State Blvd. & Wells St.	Wells St. (SB)
State Blvd. & Wells St.	State Blvd. (EB)
State Blvd. & Wells St.	State Blvd. (WB)

6. Frankfort

Intersection	Approach
Columbia St. & Clinton St.	Columbia St. (NB)
Columbia St. & Clinton St.	Columbia St. (SB)
Columbia St. & Clinton St.	Clinton St. (EB)
Columbia St. & Clinton St.	Clinton St. (WB)
Main St. & Washington St.	Main St. (NB)
Main St. & Washington St.	Main St. (SB)
Main St. & Washington St.	Washington St. (EB)
Main St. & Washington St.	Washington St. (WB)

7. Gary

Intersection	Approach
Broadway & 35th Ave.	Broadway (NB)
Broadway & 35th Ave.	Broadway (SB)
Broadway & 35th Ave.	35th Ave. (EB)
Broadway & 35th Ave.	35th Ave. (WB)
Melton Rd. & Lake St.	Lake St. (NB)
Melton Rd. & Lake St.	Lake St. (SB)
Melton Rd. & Lake St.	Melton Rd. (EB)
Melton Rd. & Lake St.	Melton Rd. (WB)

8. Hammond

Intersection	Approach
Kennedy Ave. & 165th St.	Kennedy Ave. (NB)
Kennedy Ave. & 165th St.	Kennedy Ave. (SB)
Kennedy Ave. & 165th St.	165th St. (EB)
Kennedy Ave. & 165th St.	165th St. (WB)

9. Indianapolis

Intersection	Approach
College Ave. & 86th St.	College Ave. (NB)
College Ave. & 86th St.	College Ave. (SB)
College Ave. & 86th St.	86th St. (EB)
College Ave. & 86th St.	86th St. (WB)
Kessler Blvd. & Illinois St.	Illinois St. (NB)
Kessler Blvd. & Illinois St.	Kessler Blvd. (WB)
Kessler Blvd. & Riverview Dr.	Riverview Dr. (SB)
Kessler Blvd. & Riverview Dr.	Kessler Blvd. (EB)
Moller Rd. & 34th St.	Moller Rd. (SB)
Moller Rd. & 34th St.	34th St. (EB)
Moller Rd. & 34th St.	34th St. (WB)
Shelby St. & Troy Ave.	Shelby St. (NB)
Shelby St. & Troy Ave.	Shelby St. (SB)
Shelby St. & Troy Ave.	Troy Ave. (EB)
Shelby St. & Troy Ave.	Troy Ave. (WB)
Westfield Blvd. & 86th St.	Westfield Blvd. (NB)
Westfield Blvd. & 86th St.	Westfield Blvd. (SB)
Westfield Blvd. & 86th St.	86th St. (EB)
Westfield Blvd. & 86th St.	86th St. (WB)

10. Kokomo

Intersection	Approach
Main St. & Jefferson St.	Main St. (SB)
Main St. & Jefferson St.	Jefferson St. (EB)
Markland St. & Appersonways St.	Appersonways St. (NB)
Markland St. & Appersonways St.	Appersonways St. (SB)
Markland St. & Appersonways St.	Markland St. (WB)
Monroe St. & Washington St.	Washington St. (NB)
Monroe St. & Washington St.	Washington St. (SB)
Monroe St. & Washington St.	Monroe St. (EB)
Monroe St. & Washington St.	Monroe St. (WB)
US 31 & Savoy Dr.	Savoy Dr. (EB)
US 31 & Savoy Dr.	Savoy Dr. (WB)

11. Lafayette

Intersection	Approach
Columbia St. & 9th St.	9th St. (NB)
Columbia St. & 9th St.	Columbia St. (EB)
Salem St. & 18th St.	18th St. (SB)
Salem St. & 18th St.	Salem St. (WB)
Teal Rd. & 9th St.	9th St. (NB)
Teal Rd. & 9th St.	Teal Rd. (EB)
Teal Rd. & Sequoya Dr.	Teal Rd. (WB)
Teal Rd. & 26th St.	Teal Rd. (EB)
Union St. & 9th St.	9th St. (NB)
Union St. & 9th St.	Union St. (EB)

12. Lebanon

Intersection	Approach
Main St. & West St.	West St. (NB)
Main St. & West St.	West St. (SB)
Main St. & West St.	Main St. (EB)
Main St. & West St.	Main St. (WB)

13. Logansport

Intersection	Approach
Broadway & 4th St.	4th St. (SB)
Broadway & 5th	Broadway (WB)
North St. & 6th St.	6th St. (NB)
North St. & 6th St.	6th St. (SB)
North St. & 6th St.	North St. (EB)
North St. & 6th St.	North St. (WB)

14. Mishawaka

Intersection	Approach
Lincoln Way & Ironwood Dr.	Ironwood Dr. (NB)
Lincoln Way & Ironwood Dr.	Ironwood Dr. (SB)
Lincoln Way & Ironwood Dr.	Lincoln Way (EB)
Lincoln Way & Ironwood Dr.	Lincoln Way (WB)

15. Richmond

Intersection	Approach
National Rd. & Garwood Dr.	Garwood Dr. (NB)
National Rd. & Garwood Dr.	National Rd. (WB)
National Rd. & Hayes Arboretum Dr.	Hayes Arboretum Dr. (SB)
National Rd. & Hayes Arboretum Dr.	National Rd. (EB)
National Rd. & 9th St.	National Rd. (WB)
National Rd. & 10th St.	10th St. (SB)
National Rd. & 10th St.	National Rd. (WB)

16. South Bend

Intersection	Approach
Mayflower Rd. & Sample St.	Mayflower Rd. (NB)
Mayflower Rd. & Sample St.	Mayflower Rd. (SB)
Mayflower Rd. & Sample St.	Sample St. (EB)
Mayflower Rd. & Sample St.	Sample St. (WB)
Mishawaka Ave. & Longfellow St.	Mishawaka Ave. (NB)
Mishawaka Ave. & Longfellow St.	Mishawaka Ave. (SB)
Mishawaka Ave. & Longfellow St.	Longfellow St. (EB)
Mishawaka Ave. & Longfellow St.	Longfellow St. (WB)
Western Ave. & Lombardy Dr.	Lombardy Dr. (NB)
Western Ave. & Lombardy Dr.	Lombardy Dr. (SB)
Western Ave. & Lombardy Dr.	Western Ave. (EB)
Western Ave. & Lombardy Dr.	Western Ave. (WB)

17. Terre Haute

Intersection	Approach
Hulman St. & 7th St.	7th St. (NB)
Hulman St. & 7th St.	7th St. (SB)
Hulman St. & 7th St.	Hulman St. (EB)
Hulman St. & 7th St.	Hulman St. (WB)
Poplar St. & 7th St.	7th St. (NB)
Poplar St. & 7th St.	7th St. (SB)
Poplar St. & 7th St.	Poplar St. (EB)
Poplar St. & 7th St.	Poplar St. (WB)
Wabash Ave. & 25th St.	25th St. (NB)
Wabash Ave. & 25th St.	25th St. (SB)
Wabash Ave. & 25th St.	Wabash Ave. (WB)

18. West Lafayette

Intersection	Approach
Salisbury St. & Lindberg Rd.	Salisbury St. (NB)
Salisbury St. & Lindberg Rd.	Salisbury St. (SB)
Salisbury St. & Lindberg Rd.	Lindberg Rd. (WB)
State St. & Grant St.	Grant St. (NB)
State St. & Russel St.	Russel St. (NB)
State St. & Russel St.	Russel St. (SB)

Table A-2. Cities, Intersections and Approaches from which the Data of LTOR were Collected

1. Columbus

Intersection	Approach
Brown St. & 3rd St.	Brown St. (NB)
Franklin St. & 3rd St.	Franklin St. (NB)
Lindsey St. & 8th St.	Lindsey St. (SB)

2. Fort Wayne

Intersection	Approach
Jefferson St. & Fairfield St.	Fairfield St. (SB)
Jefferson St. & Ewing St.	Jefferson St. (EB)

3. Logansport

Intersection	Approach
Broadway & 4th St.	Broadway (WB)
Broadway & 5th St.	5th St. (NB)

4. Richmond

Intersection	Approach
National Rd. & 9th St.	9th St. (NB)

Table A-3. Cities, Intersections and Approaches from which the Data of TOR Prohibition were Collected

1. Anderson

Intersection	Approach
Central Ave. & 13th St.	Central Ave. (SB)
Central Ave. & 13th St.	13th St. (WB)
Main St. & 13th St.	13th St. (WB)
Main St. & 13th St.	Main St. (NB)

2. Bloomington

Intersection	Approach
Fee Lane & 10th St.	Fee Lane (SB)
Fee Lane & 10th St.	10th St. (WB)

3. Columbus

Intersection	Approach
Washington St. & 3rd St.	3rd St. (WB)
Washington St. & 4th St.	4th St. (EB)

4. Evansville

Intersection	Approach
Market St. & Pennsylvania St.	Market St. (NB)
Market St. & Pennsylvania St.	Pennsylvania St. (WB)

5. Gary

Intersection	Approach
Lake St. & Miller Ave.	Miller Ave. (WB)
Lake St. & 7th Ave.	7th Ave. (EB)
Taft St. & 8th Ave.	8th Ave. (EB)
Taft St. & 8th Ave.	8th Ave. (WB)

6. Hammond

Intersection	Approach
Grand Ave. & 169th St.	Grand Ave. (NB)
Grand Ave. & 169th St.	Grand Ave. (SB)
Grand Ave. & 169th St.	169th St. (WB)
Parrish Ave. & 165th St.	Parrish Ave. (NB)
Parrish Ave. & 165th St.	Parrish Ave. (SB)
Parrish Ave. & 165th St.	165th St. (EB)
Parrish Ave. & 165th St.	165th St. (WB)

7. Indianapolis

Intersection	Approach
Washington St. & Oriental St.	Oriental St. (NB)
Washington St. & Oriental St.	Oriental St. (SB)
Washington St. & Oriental St.	Washington St. (WB)

8. Lebanon

Intersection	Approach
Main St. & Lebanon St.	Main St. (EB)

9. Logansport

Intersection	Approach
Linden Ave. & 6th St.	Linden Ave. (EB)
Michigan Ave. & 6th St.	6th St. (NB)

10. Richmond

Intersection	Approach
Main St. & 22nd St.	22nd St. (NB)
Main St. & 22nd St.	22nd St. (SB)
Main St. & 22nd St.	Main St. (EB)
Main St. & 22nd St.	Main St. (WB)

11. Terre Haute

Intersection	Approach
Wabash Ave. & 25th St.	Wabash Ave. (EB)

12. West Lafayette

Intersection	Approach
State St. & Brown St.	Brown St. (WB)
State St. & River Rd.	River Rd. (NB)
State St. & River Rd.	River Rd. (SB)
State St. & River Rd.	State St. (EB)
State St. & River Rd.	State St. (WB)
State St. & Russel St.	State St. (EB)

APPENDIX B

Questionnaire on RTOR and Cities Replying

QUESTIONNAIRE ON RIGHT TURN ON RED

1. What is the total number of signalized intersections in your city? _______ How many are on state highways? _____

2. What is the total number of normal 4-way signalized intersections with two-way traffic on each street that have four intersection approaches? ______________

3. What is the total number of signalized intersection approaches in your city? ___________

4. At how many of the intersection approaches listed above has right turn on red (RTOR) been prohibited? ___________

5. At those intersection approaches where RTOR has been prohibited, indicate in the table below the total number of approaches corresponding to each reason of prohibition. For example if the 25 intersection approaches in your city where RTOR is prohibited by signs, eleven (11) were so signed because of inadequate sight distance, insert the number 11 before that reason. (If an intersection approach has more than one reason for RTOR prohibition, use the most important one).

   _____ Inadequate sight distance.
   _____ The intersection has more than four approaches.
   _____ A separate signal phase for a turning movement exists at the intersection which would conflict with a RTOR movement.
   _____ There is very short red time for the approach.
   _____ Cross street traffic is heavy.
   _____ School crossing at the intersection.
   _____ Other pedestrian crossing is heavy.
   _____ Little right turn demand exists.
   _____ Others.

6. The legislation permitting RTOR has been effective in the State of Indiana since July 1, 1974. Has there been any RTOR accidents in your city since that date? _______ If yes please provide details as to why each accident occurred, severity, etc.

Please use the space below for any additional comments on RTOR.

Name and Title ____

City ________________________ State _____________________

Thank you very much for your participation.

List of Cities Replying to the Questionnaire

1. Anderson
2. Angola
3. Auburn
4. Aurora
5. Batesville
6. Bedford
7. Beech Grove
8. Berne
9. Bicknell
10. Bluffton
11. Boonville
12. Cannelton
13. Cedar Lake
14. Charlestown
15. Clinton
16. Columbia City
17. Columbus
18. Covington
19. Crawfordsville
20. Crown Point
21. Delphi
22. East Gary
23. Elkhart
24. Evansville
25. Fort Wayne
26. Frankfort
27. Gary
28. Gas City
29. Goshen
30. Greencastle
31. Greenfield
32. Greensburg
33. Greenwood
34. Hammond
35. Hartford City
36. Huntingburg
37. Jasonville
38. Knox
39. Kokomo
40. Lafayette
41. LaPorte
42. Lawrence
43. Lebanon
44. Ligonier
45. Linton
46. Loogootee
47. Marion
48. Montpelier
49. Mt. Vernon
50. Muncie
51. Nappanee
52. New Albany
53. New Castle
54. New Haven
55. Oakland City
56. Plymouth
57. Portage
58. Portland
59. Princeton
60. Rensselaer
61. Rising Sun
62. Rushville
63. Scottsburg
64. Seymour
65. South Bend
66. Sullivan
67. Tell City
68. Terre Haute
69. Union City
70. Valparaiso
71. Wabash
72. Washington
73. West Lafayette
74. Whiting

APPENDIX C

STATISTICAL ANALYSIS

APPENDIX C

STATISTICAL ANALYSIS

Models (1) and (2) in this study were based on the randomized complete block design. A restriction on randomization of the data collection occurred because each intersection approach was observed for four hours before observing other approaches. A restriction error term appeared in the two models to indicate the restriction on randomization that was imposed on the design. The restriction error has zero degrees of freedom and is completely confounded with blocks (28).

The expected mean squares of the factors of model (1) including the restriction error "δ" and the experimental error "ε" are shown in Table A-4. Tests for the effects of the factors and their interactions were indicated by arrows. All the factors are previously defined.

Model (2) was analyzed in the same manner as model (1) after replacing the term "A" by the term "S".

The peculiarity of using

$$Y_{ijk\ell m} - \beta_1 V_{1ijk\ell m} - \beta_2 V_{2ijk\ell m} - \beta_3 R_{ijk\ell m}$$

as the dependent variable in the ANOVA models really comes from multiple covariance analyses (29). Another oddity in these analyses is that the $\beta_3 R_{ijk\ell m}$ is practically constant for the four observation hours.

Table A-4. Expected Mean Squares of the Factors of Model (1)

Source	Expected Mean Square
A_i	$\sigma^2+4\sigma^2_\delta+4\sigma^2_I+16\ell\phi$ (A)
C_j	$\sigma^2+4\sigma^2_\delta+4\sigma^2_I+16\ell\phi$ (C)
AC_{ij}	$\sigma^2+4\sigma^2_\delta+4\sigma^2_I+8\ell\phi$ (AC)
Z_k	$\sigma^2+4\sigma^2_\delta+4\sigma^2_I+16\ell\phi$ (Z)
AZ_{ik}	$\sigma^2+4\sigma^2_\delta+4\sigma^2_I+8\ell\phi$ (AZ)
CZ_{jk}	$\sigma^2+4\sigma^2_\delta+4\sigma^2_I+8\ell\phi$ (CZ)
ACZ_{ijk}	$\sigma^2+4\sigma^2_\delta+4\sigma^2_I+4\ell\phi$ (ACZ)
$I_{(ijk)\ell}$	$\sigma^2+4\sigma^2_\delta+4\sigma^2_I$
$\delta_{(ijk\ell)}$	$\sigma^2+4\sigma^2_\delta$
H_m	$\sigma^2+\sigma^2_{IH}+8\ell\phi$ (H)
AH_{im}	$\sigma^2+\sigma^2_{IH}+4\ell\phi$ (AH)
CH_{jm}	$\sigma^2+\sigma^2_{IH}+4\ell\phi$ (CH)
ACH_{ijm}	$\sigma^2+\sigma^2_{IH}+2\ell\phi$ (ACH)
ZH_{km}	$\sigma^2+\sigma^2_{IH}+4\ell\phi$ (ZH)
AZH_{ikm}	$\sigma^2+\sigma^2_{IH}+2\ell\phi$ (AZH)
CZH_{jkm}	$\sigma^2+\sigma^2_{IH}+2\ell\phi$ (CZH)
$ACZH_{ijkm}$	$\sigma^2+\sigma^2_{IH}+\ell\phi$ (ACZH)
$IH_{(ijk)\ell m}$	$\sigma^2+\sigma^2_{IH}$
$\epsilon_{(ijk\ell m)}$	σ^2

COVER DESIGN BY ALDO GIORGINI